THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

SEMI-ANNUAL TECHNICAL PROGRESS REPORT April 1, 2004 - September 30, 2004

by

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Craig D. Morgan, Kevin McClure, and Roger L. Bon
Utah Geological Survey,
and
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UTAH GEOLOGICAL SURVEY

January 2005

Contract No. DE-FC26-03NT15424

Virginia Weyland, Contract Manager
U.S. Department of Energy
National Petroleum Technology Office
Williams Center Tower One
1 West 3rd Street
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DISCLAIMER

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ABSTRACT

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent producers operate and continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risks, especially in environmentally sensitive areas, and add new oil discoveries and reserves.

This report covers research and technology transfer activities for the second half of the first project year (April 1 through September 30, 2004), Budget Period I. This work included (1) core description, (2) facies characterization, and (3) diagenetic analysis of the Leadville Limestone reservoir at the Lisbon case-study field, Utah, which accounts for most of the Leadville oil production in the Paradox Basin. The reservoir characteristics, particularly diagenetic overprinting and history, and facies can be applied regionally to other fields and exploration trends in the basin.

Leadville facies include open marine (crinoidal banks or shoals and Waulsortian-type buildups), middle shelf, and restricted marine (peloid and oolitic shoals). Rock units with open-marine and restricted-marine facies constitute a significant reservoir potential, having both effective porosity and permeability when dissolution of skeletal grains, followed by dolomitization, has occurred.

Leadville reservoir quality at Lisbon is greatly enhanced by dolomitization and dissolution of limestone. There are two basic types of dolomite: very fine, early dolomite and coarse, late dolomite. Most reservoir rocks within Lisbon field appear to be associated with the second, late type of dolomitization and associated leaching events. Other diagenetic products include pyrobitumen, syntaxial cement, sulfide minerals, anhydrite cement and replacement, and late macrocalcite. Fracturing and brecciation caused by hydrofracturing are widespread within Lisbon field. Sediment-filled cavities, related to karstification of the exposed Leadville, are present in the upper third of the formation. Late dolomitization, sulfides, and brecciation may have developed from hydrothermal events that can greatly improve reservoir quality. The result can be the formation of large, diagenetic-type hydrocarbon traps further enhancing the Leadville potential in the Paradox Basin.

Technology transfer activities for the reporting period consisted of exhibiting a booth display of project materials at the annual national and regional conventions of the American Association of Petroleum Geologists, a public presentation to Grand County government officials, a technical presentation on Leadville reservoir characteristics, and publications. Project team members met with the Technical Advisory and Stake Holders Boards to review the project activities, results, and recommendations for future work, and display Leadville reservoir core. The project home page was updated on the Utah Geological Survey Web site.

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EXECUTIVE SUMMARY

The Mississippian Leadville Limestone is a shallow, open marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. These fields are currently operated by small, independent producers. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent operators continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville Limestone, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risk especially in environmentally sensitive areas, and add new oil discoveries and reserves.

To achieve this goal and carry out the Leadville Limestone study, the Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE), National Petroleum Technology Office, Tulsa, Oklahoma. The research is funded as part of the DOE Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. This report covers research and technology transfer activities for the second half of the first project year (April 1 through September 30, 2004), Budget Period I. This work included (1) core description, (2) facies characterization, and (3) diagenetic analysis of the Leadville Limestone reservoir at the Lisbon case-study field, Utah. Lisbon field accounts for most of the Leadville oil production in the Paradox Basin. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the basin.

Leadville facies include open marine (crinoidal banks or shoals and Waulsortian-type buildups), middle shelf, and restricted marine (peloid and oolitic shoals). Rock units with open-marine and restricted-marine facies constitute a significant reservoir potential, having both effective porosity and permeability when dissolution of skeletal grains, followed by dolomitization, has occurred.

Leadville reservoir quality at Lisbon is greatly enhanced by dolomitization and dissolution of limestone. There are two basic types of dolomite: very fine, early dolomite and coarse, late dolomite. Early dolomitization preserves depositional fabrics and has limited porosity development, except for limited dissolution of fossils, and exhibits very low permeabilities. Late dolomitization has two morphologies: rhombic dolomites and saddle dolomites. Most reservoir rocks within Lisbon field appear to be associated with the second, late type of dolomitization and associated leaching events.

Pyrobitumen coats most intercrystalline dolomite, as well as dissolution pores associated with the second type of dolomite. Fracturing and brecciation caused by hydrofracturing are widespread within Lisbon field. Sediment-filled cavities, related to karstification of the exposed Leadville, are relatively common throughout the upper third of the formation in the field. Other diagenetic products include syntaxial cement, sulfide minerals, anhydrite cement and replacement, and late macrocalcite.

Late dolomitization, saddle dolomite, and dolomite cement precipitation, as well as sulfides and brecciation, may have developed from hydrothermal events that can greatly improve reservoir quality. The result can be the formation of large, diagenetic-type, hydrocarbon traps. Further geochemical analysis is needed confirm the presence of

hydrothermal dolomite in the Leadville Limestone at Lisbon field and the potential it would imply for the Paradox Basin.

Technology transfer activities for the reporting period consisted of a non-technical presentation to the Grand County Council, members of the press, and general public. The petroleum geology of the Paradox Basin and an overview of project goals, activities, and results were part of the presentation. Project materials, plans, objectives, and results were displayed at the Utah Geological Survey booth during the American Association of Petroleum Geologists (AAPG) Annual Convention, April 18-24, 2004, in Dallas, Texas, and at the AAPG Rocky Mountain Section Meeting/Rocky Mountain Natural Gas Strategy Conference and Investment Forum, August 9-11, 2004, in Denver, Colorado. A technical presentation was made at the Denver meeting discussing general petroleum geology of the Leadville Limestone, and facies, petrography, and diagenesis of the Lisbon case-study field in Utah. Project team members also met with the Technical Advisory and Stake Holders Boards to review the project activities, results, and recommendations for future work, and display reservoir core from the Lisbon field. The project home page was updated on the Utah Geological Survey Web site. Project team members published an abstract and semi-annual report detailing project progress and results.

INTRODUCTION

Project Overview

The Mississippian Leadville Limestone has produced over 53 million barrels (bbls) (8.4 million m^3) of oil from six fields in the northern Paradox Basin region, referred to as the Paradox fold and fault belt, of Utah and Colorado. All of these fields are currently operated by small, independent producers. There have been no new discoveries since the early 1960s, and only independent producers continue to explore for Leadville oil targets in the region, 85 percent of which is under the stewardship of the federal government. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored with only about 100 exploratory wells that penetrated the Leadville (less than one well per township), and thus the potential for new discoveries remains great.

The overall goals of this study are to (1) develop and demonstrate techniques and exploration methods never tried on the Leadville Limestone, (2) target areas for exploration, (3) increase deliverability from new and old Leadville fields through detailed reservoir characterization, (4) reduce exploration costs and risk especially in environmentally sensitive areas, and (5) add new oil discoveries and reserves.

The Utah Geological Survey (UGS) and Eby Petrography & Consulting, Inc., have entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. The project will be conducted in two phases, each with specific objectives and separated by a continue-stop decision point based on results as of the end of Phase I. The objective of Phase 1 is to conduct a case study of the Leadville reservoir at Lisbon field (the largest Leadville producer), San Juan County, Utah, in order understand the reservoir characteristics and facies that can be applied regionally. The first objective of Phase 2 will be to conduct a low-cost field demonstration of new exploration technologies to identify potential Leadville oil migration directions (evaluating the middle Paleozoic hydrodynamic pressure regime), and surface geochemical anomalies (using microbial, soil, gas, iodine, and trace elements), especially in environmentally sensitive areas. The second objective will be to determine regional facies (evaluating cores, geophysical well logs, outcrop and modern analogs), identify potential oil-prone areas based on shows (using low-cost epifluorescence techniques), and target areas for Leadville exploration.

These objectives are designed to assist the independent producers and explorers who have limited financial and personnel resources. All project maps, studies, and results will be publicly available in digital (interactive, menu-driven products on compact disc) or hard-copy format and presented to the petroleum industry through a proven technology transfer plan. The technology transfer plan includes a Technical Advisory Board composed of industry representatives operating in the Paradox Basin and a Stake Holders Board composed of representatives of state and federal government agencies, and groups with a financial interest within the study area. Project results will also be disseminated via the UGS Web site, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, convention displays, and papers in various technical or trade journals, and UGS publications.

This report covers research and technology transfer activities for the second half of the first project year (April 1 through September 30, 2004), Budget Period I. This work included (1) core description, (2) facies characterization, and (3) diagenetic analysis of the Leadville Limestone reservoir at the Lisbon case-study field, Utah.

Project Benefits and Potential Application

Exploring for the Leadville Limestone is high risk, with less than a 10 percent chance of success based on the drilling history of the region. Prospect definition requires expensive, three-dimensional (3D) seismic acquisition, often in environmentally sensitive areas. These facts make exploring difficult for independents that have limited funds available to try new, unproven techniques that might increase the chance of successfully discovering oil. We believe that one or more of the project activities will reduce the risk taken by an independent producer in looking for Leadville oil, not only in exploring but in trying new techniques. For example, the independent would not likely attempt surface geochemical surveys without first knowing they have been proven successful in the region. If we can prove geochemical surveys are an effective technique in environmentally sensitive areas, the independent will save both time and money exploring for Leadville oil.

Another problem in exploring for oil in the Leadville Limestone is the lack of published or publicly available geologic and reservoir information, such as regional facies maps, complete reservoir characterization studies, surface geochemical surveys, regional hydrodynamic pressure regime maps, and oil show data and migration interpretations. Acquiring this information or producing these studies would save cash and manpower resources which independents simply do not possess or normally have available only for drilling. The technology, maps, and studies generated from this project will help independents to identify or eliminate areas and exploration targets prior to spending significant financial resources on seismic data acquisition and environmental litigation, and therefore increase the chance of successfully finding new accumulations of Leadville oil.

These benefits may also apply to other high-risk, sparsely drilled basins or regions where there are potential shallow-marine carbonate reservoirs equivalent to the Mississippian Leadville Limestone. These areas include the Utah-Wyoming-Montana thrust belt (Madison Limestone), the Kaiparowits Basin in southern Utah (Redwall Limestone), the Basin and Range Province of Nevada and western Utah (various Mississippian and other Paleozoic units), and the Eagle Basin of Colorado (various Mississippian and other Paleozoic units).

Many mature basins have productive carbonate reservoirs of shallow-marine shelf origin. These mature basins include the Eastern Shelf of the Midland Basin, West Texas (Pennsylvanian-age reservoirs in the Strawn, Canyon, and Cisco Formations); the Permian Basin, West Texas and southeast New Mexico (Permian age Abo and other formations along the northwest shelf of the Permian Basin); and the Illinois Basin (various Silurian units). A successful demonstration in the Paradox Basin makes it very likely that the same techniques could be applied in other basins as well. In general, the average field size in these other mature basins is larger than fields in the Paradox Basin. Even though there are differences in depositional facies and structural styles between the Paradox Basin and other basins, the fundamental use of the techniques and methods is a critical commonality.

PARADOX BASIN - OVERVIEW

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with a small portion in northeastern Arizona and northwestern New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian. The basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the Aneth platform in southeasternmost Utah (figure 1). The Mississippian Leadville Limestone is one of two major oil and gas reservoirs in the Paradox Basin, the other being the Pennsylvanian Paradox Formation (figure 2). Most Leadville production is from the Paradox fold and fault belt (figure 3).

The most obvious structural features in the basin are the spectacular anticlines that extend for miles in the northwesterly trending fold and fault belt. The events that caused these and many other structural features to form began in the Proterozoic, when movement initiated on high-angle basement faults and fractures 1700 to 1600 Ma (Stevenson and Baars, 1987). During Cambrian through Mississippian time, this region, as well as most of eastern Utah, was the site of typical, thin, marine deposition on the craton while thick deposits accumulated in the miogeocline to the west (Hintze, 1993). However, major changes occurred beginning in the Pennsylvanian. A series of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The southwestern flank of the Uncompahgre Highlands (uplift) is bounded by a large, basement-involved, high-angle, reverse fault identified from seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest – the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993).

The Paradox Basin is surrounded by other uplifts and basins, which formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1). The Paradox fold and fault belt was created during the Tertiary and Quaternary by a combination of (1) reactivation of basement normal faults, (2) salt flowage, dissolution and collapse, and (3) regional uplift (Doelling, 2000).

Most oil and gas produced from the Leadville Limestone is found in basement-involved, northwest-trending structural traps with closure on both anticlines and faults (figure 4). Lisbon, Big Indian, Little Valley, and Lisbon Southeast fields (figure 3) are sharply folded anticlines that close against the Lisbon fault zone. Salt Wash and Big Flat fields (figure 3), northwest of the Lisbon area, are unfaulted, east-west- and north-south-trending anticlines, respectively.

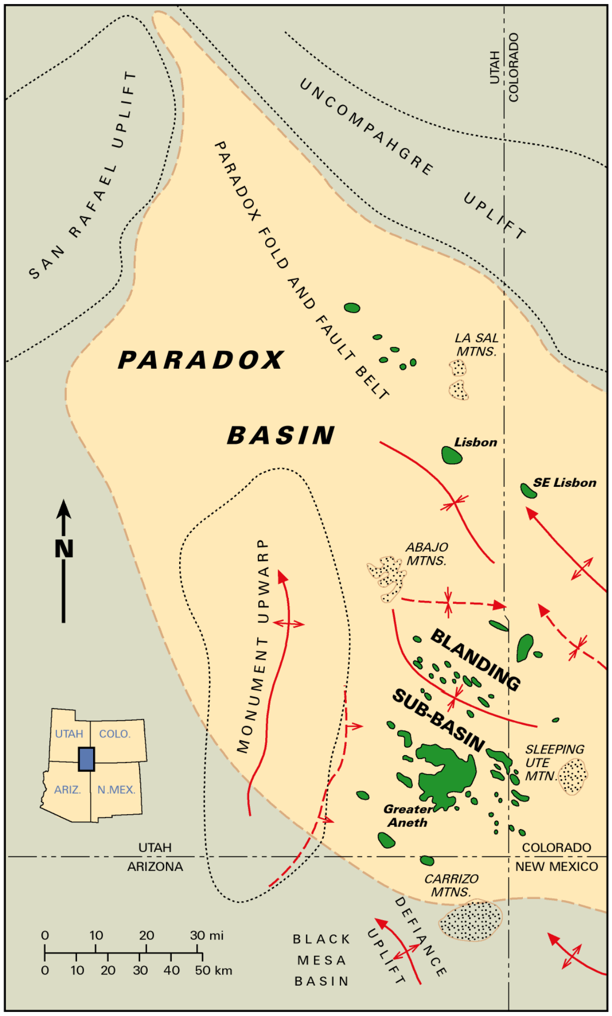


Figure 1. Oil and gas fields in the Paradox Basin of Utah and Colorado.

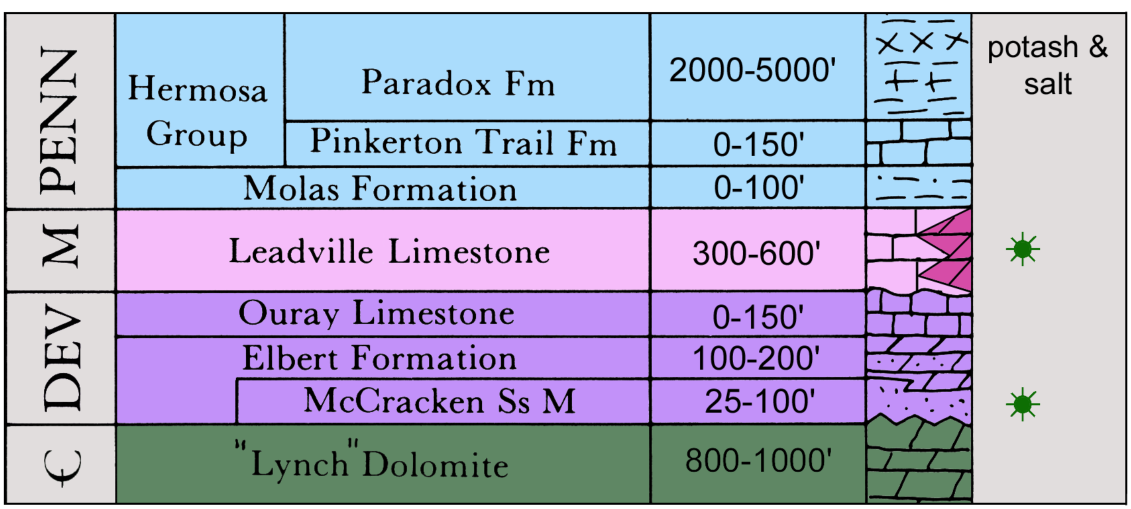


Figure 2. Stratigraphic column of a portion of the Paleozoic section determined from subsurface well data in the Paradox fold and fault belt, Grand and San Juan Counties, Utah (modified from Hintze, 1993).

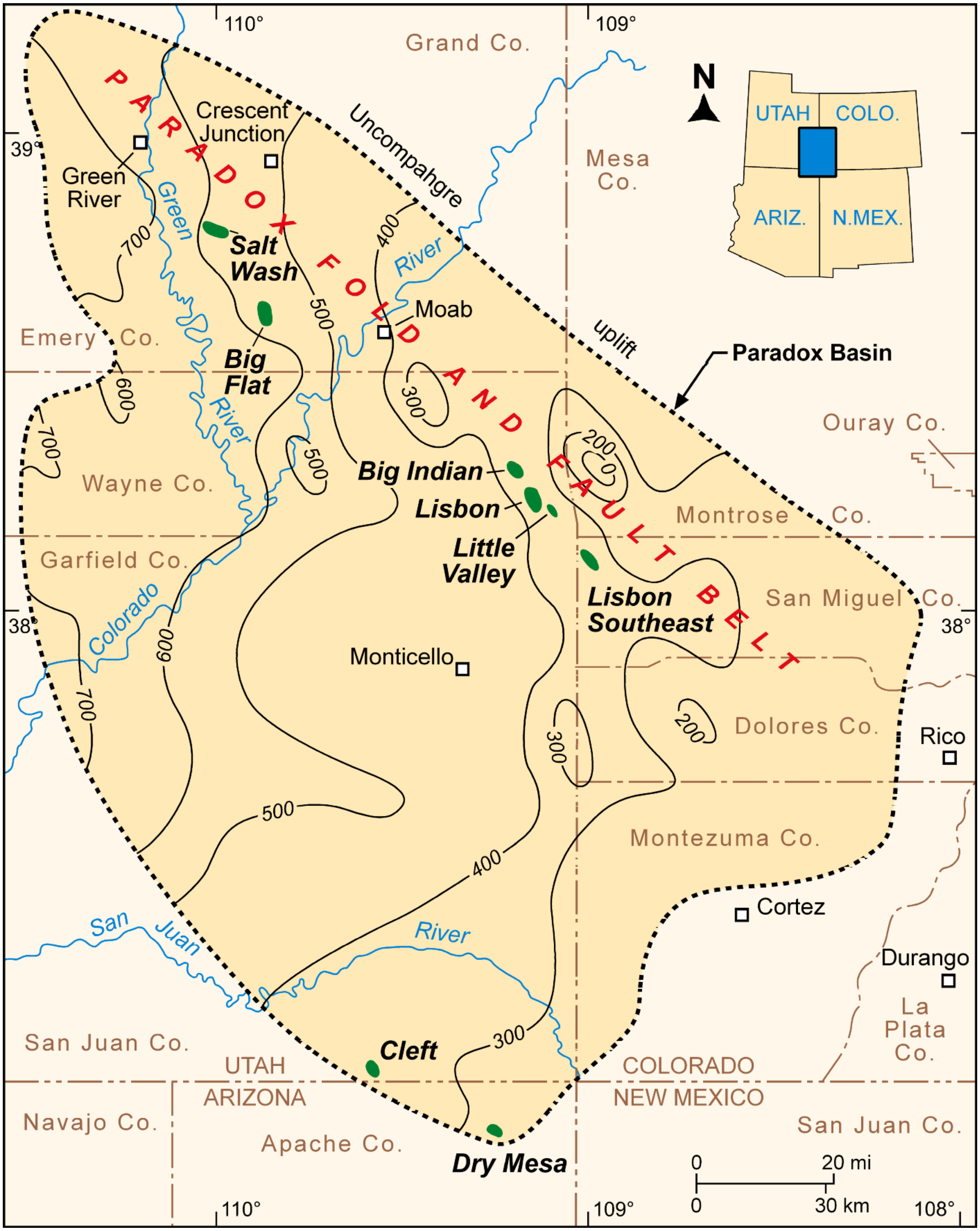


Figure 3. Location of fields that produce oil (green) from the Mississippian Leadville Limestone, Utah and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963).

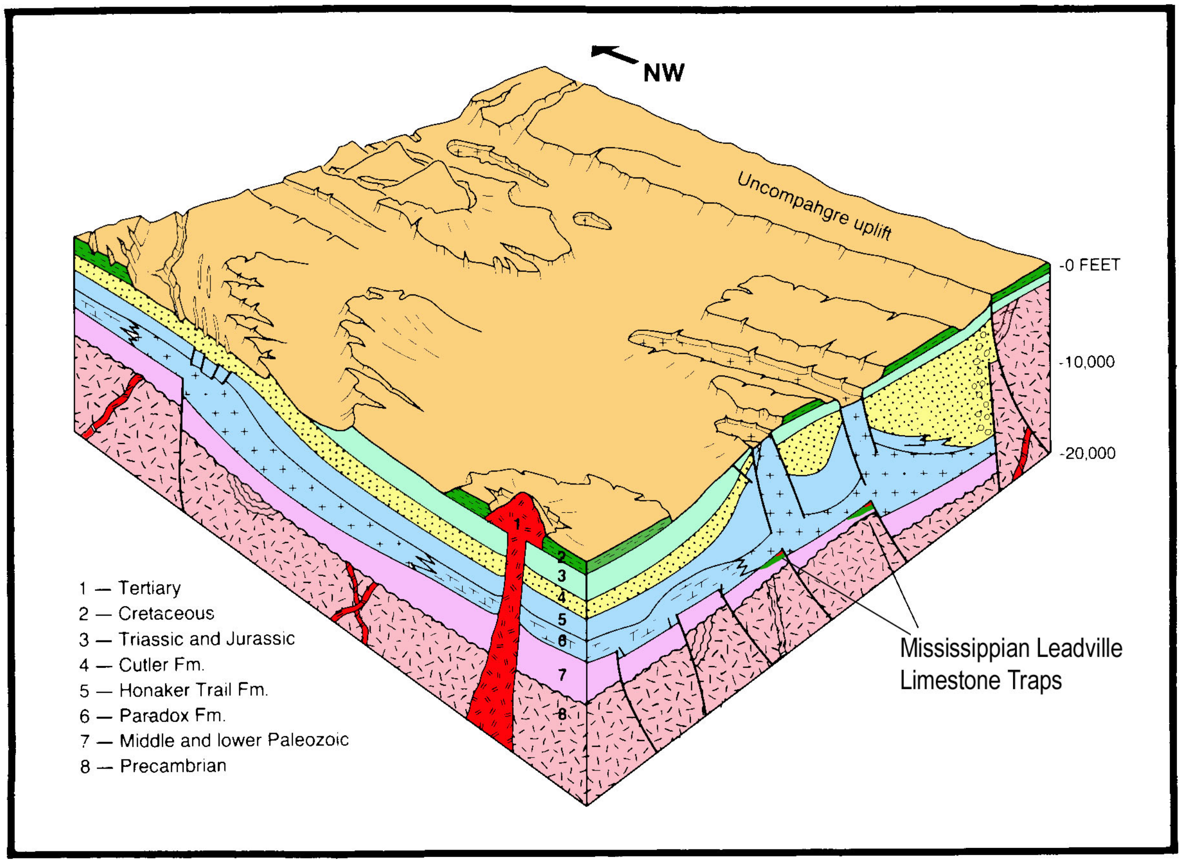


Figure 4. Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).

RESERVOIR CHARACTERIZATION OF THE LEADVILLE LIMESTONE, LISBON CASE-STUDY FIELD, SAN JUAN COUNTY, UTAH – RESULTS AND DISCUSSION

Introduction and Field Synopsis

Lisbon field, San Juan County, Utah (figure 3) accounts for most of the Leadville oil production in the Paradox Basin. A wealth of Lisbon core, petrographic, and other data is available to the UGS. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the Paradox Basin. Therefore, we selected Lisbon as the major case-study field for the Leadville Limestone project.

The Lisbon trap is an elongate, asymmetric, northwest-trending anticline, with nearly 2000 feet (600 m) of structural closure and bounded on the northeast flank by a major, basement-involved normal fault with over 2500 feet (760 m) of displacement (Smith and Prather, 1981) (figure 5). Several minor, northeast-trending normal faults dissect the Leadville reservoir into segments. Producing units contain dolomitized crinoidal/skeletal grainstone, packstone, and wackestone fabrics. Diagenesis includes fracturing, autobrecciation, karst development, hydrothermal dolomite, and bitumen plugging. The net reservoir thickness is 225 feet (69 m) over a 5120-acre (2100 ha) area (Clark, 1978; Smouse, 1993). Reservoir quality is greatly improved by natural fracture systems associated with the Paradox fold and fault belt. Porosity averages 6 percent in intercrystalline and moldic networks enhanced by fractures; permeability averages 22 millidarcies (mD). The drive mechanism is an expanding gas cap and gravity drainage; water saturation is 39 percent (Clark, 1978; Smouse, 1993). The bottom-hole temperature ranges from 153 to 189ºF (53-73ºC).

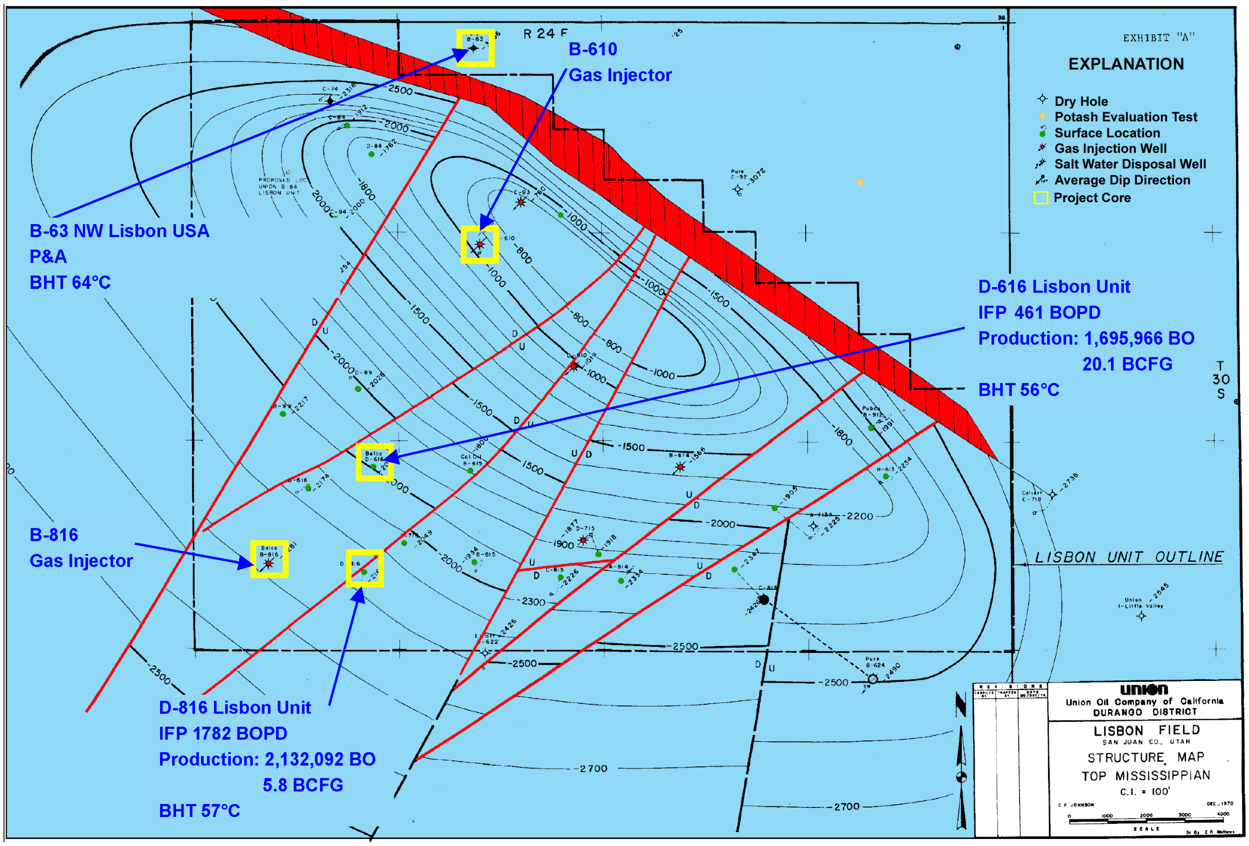


Figure 5. Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah (modified from C.F. Johnson, Union Oil Company of California files, 1970; courtesy of Tom Brown, Inc.). Also displayed are wells from which cores were described in this study.

Lisbon field was discovered in 1960 with the completion of the Pure Oil Company No. 1 NW Lisbon USA well, NE1/4NW1/4 section 10, T. 30 S., R. 24 E., Salt Lake Base Line and Meridian (SLBL&M) (figure 5), with an initial flowing potential (IFP) of 179 bbls of oil per day (BOPD) (28 m^3) and 4376 thousand cubic feet of gas per day (MCFGPD) (124 MCMPD). The original reservoir field pressure was 2982 pounds per square inch (psi) (20,560 kPa) (Clark, 1978). There are currently 22 producing (or shut-in wells), 11 abandoned producers, five injection wells (four gas injection wells and one water/gas injection well), and four dry holes in the field. Cumulative production as of August 1, 2004, was 51,098,895 bbls of oil (812,472 m^3), 769.8 billion cubic feet of gas (BCFG) (21.8 BCMG) (cycled gas), and 49,738,983 bbls of water (7,908,498 m^3) (Utah Division of Oil, Gas and Mining, 2004). The oil and gas characteristics are summarized on table 1. Gas that was re-injected into the crest of the structure to control pressure decline is now being produced.

Three factors create reservoir heterogeneity within productive zones: (1) variations in carbonate fabrics and facies, (2) diagenesis (including karstification), and (3) fracturing. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow.

Table 1. General characteristics of the oil and gas produced from the Leadville Limestone at Lisbon field, San Juan County, Utah (Stowe, 1972; Morgan, 1993; UGS oil sample bank database).

Oil		Gas	
Gravity	54-62.6° API	Methane	48%
Specific Gravity	0.765	Higher Fractions	13%
Color	Yellow to Red	Nitrogen	24%
Pour Point	-35°F	Carbon Dioxide	14%
Viscosity (cst)*	1.03 @ 104°F	Hydrogen Sulfide	1.2%
Viscosity (sus)†	29.2 @ 104°F	Helium	trace-1.1%
Sulfur	0.2%	Specific Gravity	0.89
Nitrogen	0.002%	Heating Value	685 BTU/ft^3

* centistokes
† Saybolt Universal Seconds

Data Collection and Compilation

Geophysical well logs, cores and cuttings, reservoir data, various reservoir maps, and other information from regional exploratory and field development wells are being collected by the UGS. Well locations, formation tops, production data, completion tests, basic core analysis, porosity and permeability data, and other data are being compiled and entered in a database developed by the UGS. This database, INTEGRAL, is a geologic-information database that links a diverse set of geologic data to records using MS Access™. The database is designed so that geological information, such as lithology, petrophysical analyses, or depositional environment, can be exported to software programs to produce cross sections, strip logs, lithofacies maps, various graphs, and other types of presentations. The database containing information on the geological reservoir characterization case study as well as later regional correlations will be available at the UGS's Leadville Limestone project Web site at the conclusion of the project.

Core Description

All available conventional cores from Lisbon field (figure 5) were photographed and described (table 2). Special emphasis was placed on identifying the flow unit's bounding surfaces and depositional environments. The core descriptions follow the guidelines of Bebout and Loucks (1984), which include (1) basic porosity types, (2) mineral composition in percentage, (3) nature of contacts, (4) carbonate structures, (5) carbonate textures in percentage, (6) carbonate fabrics, (7) grain size (dolomite), (8) fractures, (9) color, (10) fossils, (11) cement, and (12) depositional environment. Carbonate fabrics were determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes.

Table 2. List of well conventional slabbed core examined and described from the Leadville Limestone, Lisbon field, San Juan County, Utah.*

Well	Location	API No.	Core Interval (feet)	Thin Sections
Lisbon D-816	NE SE 16, T. 30 S., R. 24 E.	43-037-16253	8417-8450	15
Lisbon D-616	C NE NE 16, T. 30 S., R. 24 E.	43-037-15049	8300-9110	13
NW Lisbon B-63	NE NW 3, T. 30 S., R. 24 E.	43-037-11339	9934-10,005	14
Lisbon B-816	NE SW 16, T. 30 S., R. 24 E.	43-037-16244	8463-8697	22
Lisbon B-610	NE NW 10, T. 30 S., R. 24 E.	43-037-16469	7590-8001.5	18

*Repository: Utah Core Research Center.

Geological characterization on a local scale focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible compartmentalization within Lisbon field. This utilized representative core and modern geophysical well logs to characterize and initially grade various untested intervals in the field for possible additional completion attempts.

The typical vertical sequence or cycle of lithofacies from Lisbon field, as determined from conventional core, was tied to its corresponding log response (figure 6). These sequences graphically include (1) carbonate fabric, pore type, physical structures, texture, framework grain, and facies described from core; (2) plotted porosity and permeability analysis from core plugs; and (3) gamma-ray and neutron-density curves from geophysical well logs. The graphs can be used for identifying reservoir and non-reservoir rock, determining potential untested units suitable for completion or possible horizontal drilling projects, and comparing field to non-field areas.

Leadville Facies

Regional Characteristics

The Mississippian (late Kinderhookian through Osagean to early Meramecian time) Leadville Limestone is a shallow, open marine, carbonate-shelf deposit (figure 7). The western part of the Paradox fold and fault belt includes a regional, reflux-dolomitized, interior bank facies containing Waulsortian mounds (Welsh and Bissell, 1979). During Late Mississippian time, the entire carbonate platform in southeastern Utah and southwestern Colorado was subjected to subaerial erosion resulting in formation of a lateritic regolith (Welsh and Bissell, 1979). This regolith and associated carbonate dissolution is an important factor in Leadville reservoir potential (figure 8). Solution breccia and karstified surfaces are common, including possible local development of cavernous zones (Fouret, 1982, 1996).

The Leadville Limestone thins from more than 700 feet (230 m) in the northwest corner of the Paradox Basin to less than 200 feet (70 m) in the southeast corner (Morgan, 1993) (figure 3). Thinning is a result of both depositional onlap onto the Mississippian cratonic shelf and erosion. The Leadville is overlain by the Pennsylvanian Molas Formation and underlain by the Devonian Ouray Limestone (figure 2).

Periodic movement along northwest-trending faults affected deposition of the Leadville Limestone. Crinoid banks or mounds, the primary reservoir facies (figure 7), accumulated in shallow-water environments on upthrown fault blocks or other paleotopographic highs. In areas of greatest paleorelief, the Leadville is completely missing as a result of non-deposition or subsequent erosion (Baars, 1966).

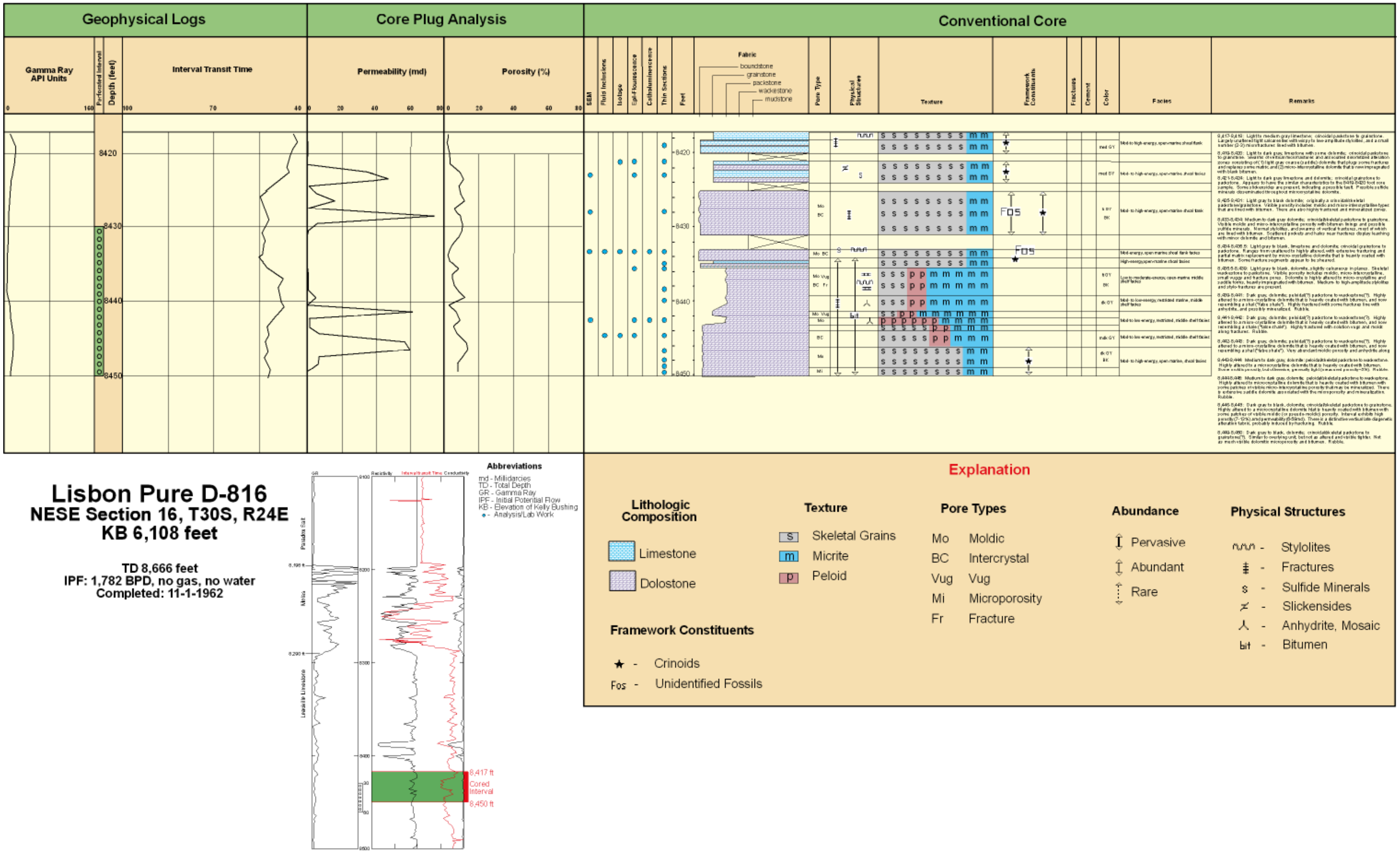


Figure 6. Typical Leadville vertical sequence from Lisbon field, including geophysical well logs, porosity/permeability plots, and core description, of the Lisbon Pure No. D-816 well (figure 5), San Juan County, Utah.

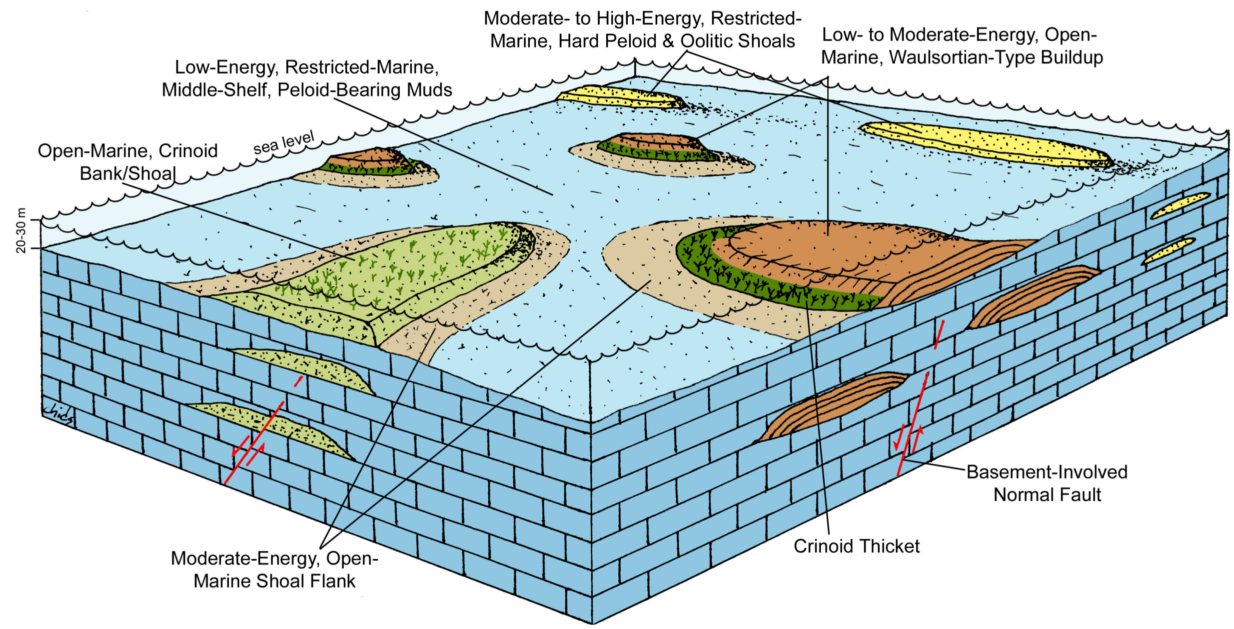


Figure 7. Block diagram displaying major depositional facies, as determined from core, for the Leadville Limestone, Lisbon field, San Juan County, Utah.

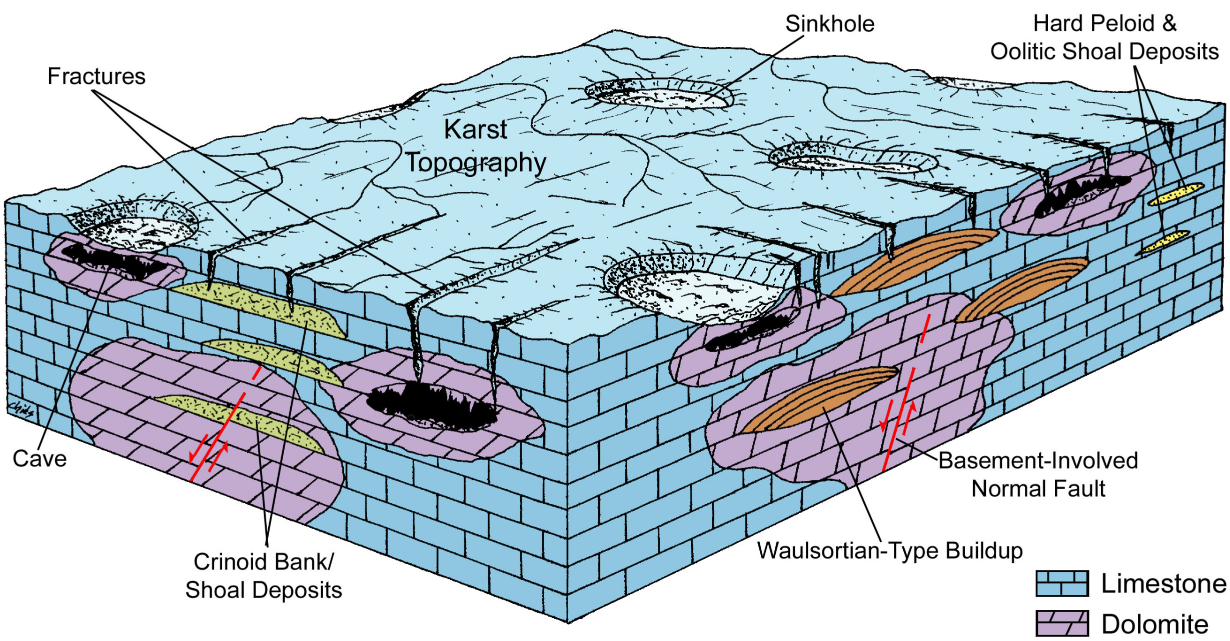


Figure 8. Block diagram displaying post-Leadville karst and fracture overprint.

The Leadville Limestone is divided into two members separated by an intraformational disconformity. The dolomitic lower member is composed of mudstone, wackestone, packstone, and grainstone deposited in shallow-marine, subtidal, supratidal, and intertidal environments (Fouret, 1982, 1996). Fossils include crinoids, fenestrate bryozoans, and brachiopods. Locally, mud-supported boundstone creates buildups or mud mounds (Waulsortian facies), involving growth of “algae” (Wilson, 1975; Ahr, 1989; Fouret, 1982, 1996). The upper member is composed of mudstone, packstone, grainstones (limestone and dolomite), and terrigenous clastics also deposited in subtidal, supratidal, and intertidal environments (Fouret, 1982, 1996). Fossils include crinoids and rugose coral. Reservoir rocks are crinoid-bearing packstone (Baars, 1966).

Field Facies

Three depositional facies have been identified from Leadville Limestone cores we described from the Lisbon case-study field (figure 7). Recognizing and mapping of these facies regionally will delineate prospective reservoir trends containing porous and productive buildups or zones. Leadville facies include open marine, middle shelf, and restricted marine.

Open marine: Open-marine facies are represented by crinoidal banks or shoals and Waulsortian-type buildups (figure 7). Crinoidal banks and shoals are common throughout Leadville deposition, often located on paleotopographic highs developed along the upthrown side of older basement-involved faults. This facies represents a high-energy environment with well-circulated, normal-marine salinity water in a subtidal setting. Wave action was strong (leaving broken crinoid columns and winnowing out mud) to moderate (leaving articulated crinoid columnals and some muddy matrix). Low to medium cross-bedding is common. Crinoid columnals were not transported far from the thickets where they grew. Rugose corals were also abundant in this environment. According to Wilson (1975), crinoid columnals or segments were covered with organic matter which allowed them to float until accumulating on nearby shoals and banks. Water depths ranged from 5 feet to 45 feet (1.5-14 m). The depositional fabrics of crinoidal banks and shoals include grainstone and packstone (figure 9). Rocks representing crinoidal banks and shoals typically contain the following diagnostic constituents: dominately crinoids and rugose corals, and lesser amounts of broken fenestrate bryozoans, brachiopods, ostracods, and endothyroid forams as skeletal debris. Rock units having this facies constitute a significant reservoir potential, having both effective porosity and permeability when dissolution of skeletal grains, followed by dolomitization, has occurred.

Waulsortian buildups or mud mounds developed exclusively during the Mississippian in many parts of the world (Wilson, 1975) and Waulsortian-type buildups were first described in Lisbon field by Fouret (1982). They are steep-sloped tabular, knoll, or sheet forms composed of several generations of mud deposited in a subtidal setting (Lees and Miller, 1995; Fouret, 1982, 1996) (figure 7). The lime mud was precipitated by bacteria and fungal/cyanobacterial filaments (Lees and Miller, 1995). Cyanobacteria was a likely precursor to the green algae *Ivanovia* responsible for Pennsylvanian buildups in the Paradox Basin (Fouret, 1982, 1996). Crinoids and sheet-like fenestrate byrozoans, in the form of thickets, are associated with the deeper parts of the mud mounds and are indicative of well-circulated, normal-marine salinity. Water depths ranged from 60 to 90 feet (20-30 m). The thickets surrounded and helped to stabilize the mound. Burrowing organisms added a pelletal component to the mud, and

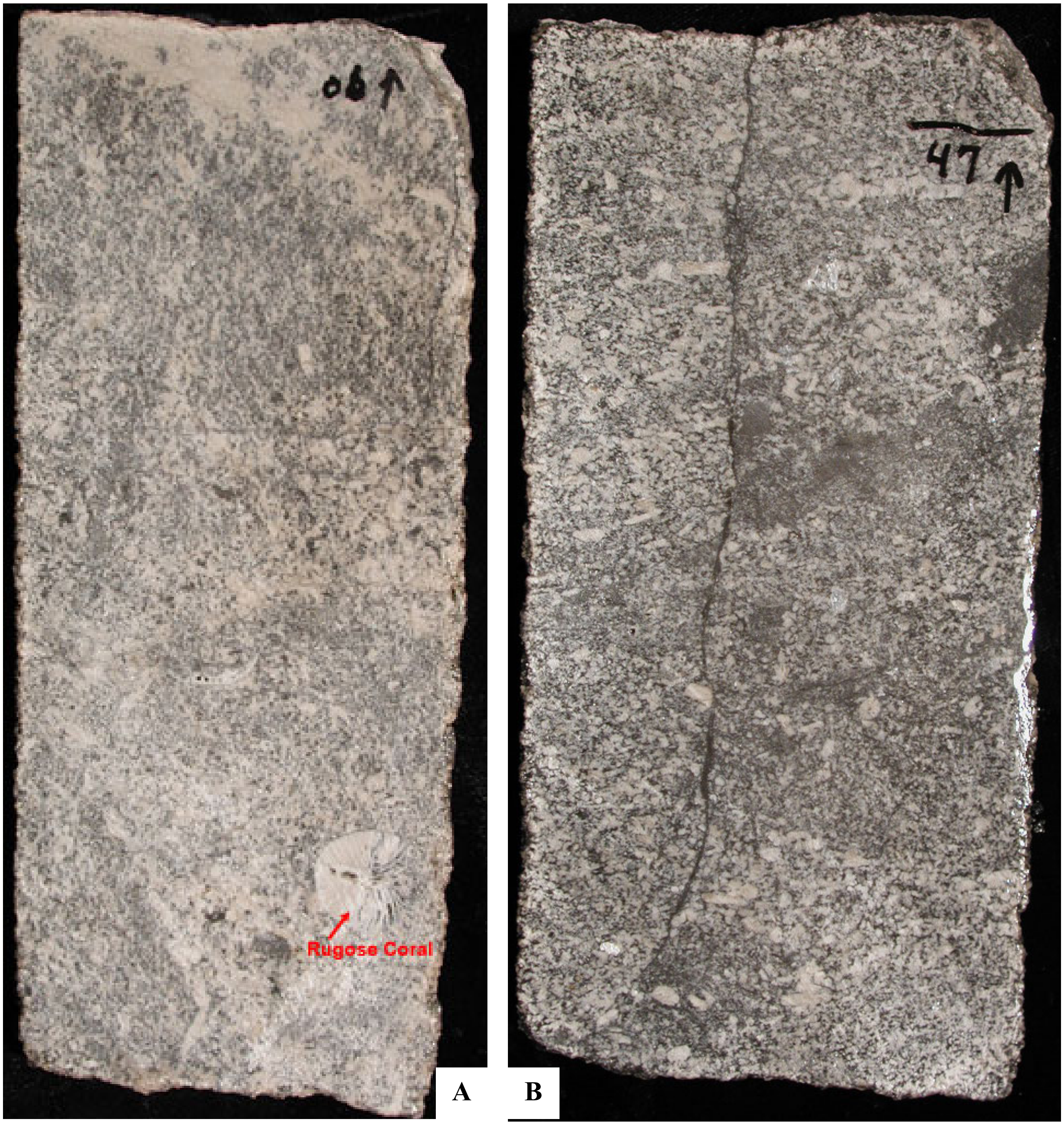


Figure 9. Typical crinoidal/skeletal grainstone/packstones representing high-energy, open-marine shoal facies, Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 5]). (A) Slabbed core from 8506.5 feet. Note the large rugose coral. (B) Slabbed core from 8547 feet.

burrowing often destroyed laminations or made them discontinuous. Individual mounds range from a few feet to tens of feet thick, and cover hundreds of feet in area with distinctive flank deposits. They form thick, extensive aggregates often located on paleotopographic highs associated with basement-involved faults (figure 7). This facies represents a low- to moderate-energy environment. The depositional fabrics of the Waulsortian-type buildups include mud-supported boundstone, packstone, and wackestone (figure 10). Rocks representing

Figure 10. Typical peloidal/skeletal packstone/wackestones representing moderate- to low-energy, open-marine, Waulsortian-type buildup facies. (A) Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 5]); slabbed core from 8646 feet. (B) Lisbon No. D-616 (NE1/4NE1/4 section 16, T. 30 S., R. 24 E., SLBL&M); slabbed core from 8514 feet.

Waulsortian-type buildups typically contain the following diagnostic constituents: peloids, crinoids, bryozoans, and associated skeletal debris, and *stromatactis*. Rock units having this facies constitute a significant reservoir potential, having both effective porosity and permeability, especially after dolomitization. Waulsortian-type buildups are recognized in several additional cores described by Fouret (1982, 1996).

Shoal-flank facies are associated with both crinoid bank/shoal and Waulsortian-type buildup facies (figure 7). This facies represents a moderate-energy environment, again with well-circulated, normal-marine salinity water in a subtidal setting. Water depths ranged from 60 to 90 feet (20-30 m). In the shallower areas, wave action was strong to moderate, eroding the flanks of the shoals and mud mounds into a breccia. Bedding is generally absent in cores. The depositional fabrics of the shoal-flank facies include peloidal/skeletal packstone and wackestone (figure 11). Rocks representing this facies typically contain the following diagnostic constituents: peloids, crinoids, bryozoans, brachiopods, and associated skeletal debris, and talus, depositional breccia, and conglomerate (Fouret, 1982, 1996). Rock units having shoal-flank facies constitute a limited reservoir potential, having little effective porosity and permeability.

Restricted marine: Restricted-marine facies are represented by "hard" peloid and oolitic shoals that developed as a result of regularly agitated, shallow-marine processes on the shelf (figure 7). Like crinoidal banks and Waulsortian-type buildups, hard peloid and oolitic shoals are common throughout Leadville deposition, especially on paleotopographic highs. This facies represents a moderate- to high-energy environment, with moderately well-circulated water in an intertidal setting. The water probably had slightly elevated salinity compared to the other facies. Sediment deposition and modification probably occurred in water depths ranging from near sea level to 20 feet (6 m) below sea level. Wave action winnowed out mud leaving various well-sorted grains. Characteristic features of this facies include medium-scale cross-bedding and bar-type carbonate sand-body morphologies that formed not only shoals, but beaches and tidal bars (Fouret, 1982). Well-developed ooids were produced from movement of particles over algal or cyanobacterial mats by intertidal currents and continuous wave action (Mitchell, 1961; Fouret, 1982).

The depositional fabrics of the restricted-marine facies include grainstone and packstone (figure 12). Rocks representing this facies typically contain the following diagnostic constituents: ooids, coated grains, and hard pelloids. Fossils are relatively rare.

Rock units having restricted-marine facies constitute good reservoir potential. Remnants of visible interparticle and moldic porosity may be present in this facies. Dolomitization significantly increases the reservoir quality of this facies.

Middle shelf: Middle-shelf facies covered extensive areas across the shallow shelf. This facies represents a low-energy, often restricted-marine environment (figure 7). Mud and some sand were deposited in subtidal (burrowed), inter-buildup/shoal setting. Water depths ranged from 60 to 90 feet (20-30 m).

The depositional fabrics of the middle-shelf facies include wackestone and mudstone (figure 13). The most common is bioturbated lime to dolomitic mudstone with sub-horizontal feeding burrows. Rocks representing this facies typically contain the following diagnostic constituents: soft pellet muds, "soft" peloids, grain aggregates, crinoids and associated skeletal debris, and fusulinids.

Figure 11. Typical peloidal/skeletal packstone/wackestone representing moderate-energy, open-marine, shoal-flank facies. Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 5]); slabbed core from 8521 feet.

Figure 12. Typical peloidal grainstone/packstone representing moderate-energy, restricted-marine, "hard" peloid shoal facies. Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 5]); slabbed core from 8463 feet.

Figure 13. Typical skeletal/"soft" peloidal wackestone/mudstone representing low-energy, restricted-marine, middle-shelf facies. Lisbon No. B-816 (NE1/4SW1/4 section 16, T. 30 S., R. 24 E., SLBL&M [figure 5]); slabbed core from 8549 feet.

Rock units having middle-shelf facies act as barriers and baffles to fluid flow, having very little effective porosity and permeability. There are few megafossils and little visible matrix porosity, with the exception of an occasional moldic pore. However, recognizing this facies is important because low-energy carbonates of the middle shelf form the substrate for the development of the higher energy crinoid banks, oolitic/hard peloid shoals, and Waulsortian-type buildups (figure 7). The middle-shelf facies can contain reservoir-quality rocks if dolomitized.

Diagenetic Analysis

Techniques

The diagenetic fabrics and porosity types found in the various hydrocarbon-bearing rocks of Lisbon field can be indicators of reservoir flow capacity, storage capacity, and untested potential. In order to determine the diagenetic histories of the various Leadville rock fabrics, including both reservoir and non-reservoir, 64 thin sections of representative samples were selected from the conventional cores for petrographic description and possible geochemical analysis. Carbonate fabrics were again determined according to Dunham's (1962) and Embry and Klovan's (1971) classification schemes. Pores and pore systems were described using Choquette and Pray's (1970) classification (figure 14). Each thin section was photographed with additional close-up photos of (1) typical preserved primary and secondary pore types, (2) cements, (3) sedimentary structures, (4) fractures, and (5) where present, pore-plugging anhydrite and halite.

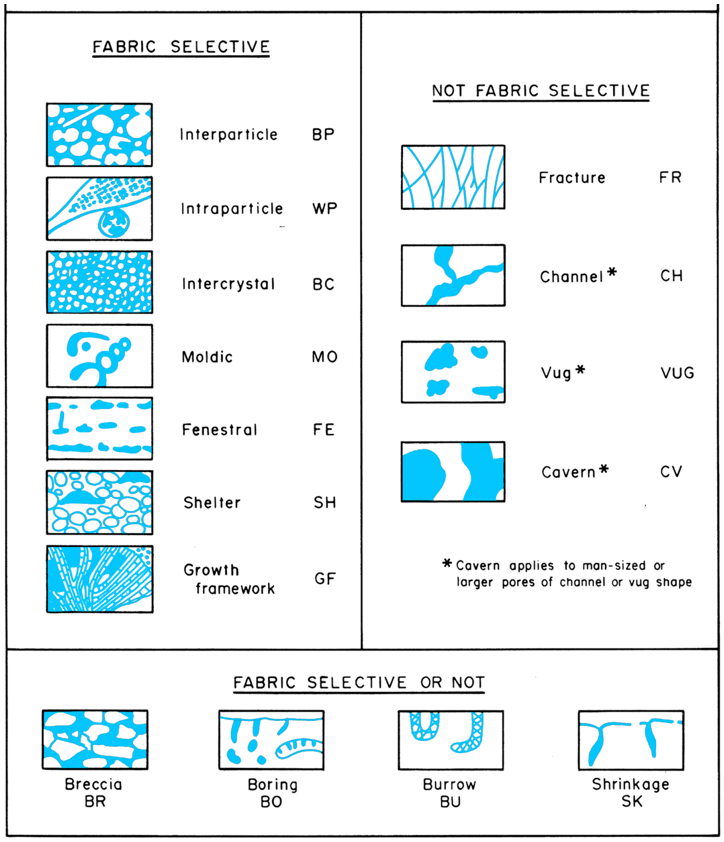


Figure 14. Classification of pores and pore systems in carbonate rocks (Choquette and Pray, 1970).

Typical geochemical and petrographic techniques that may be later employed include (1) epifluorescence and cathodoluminescence petrography for the sequence of diagenesis, (2) stable carbon and oxygen isotope analysis of diagenetic components such as cementing minerals and different generations of dolomites, (3) strontium isotopes for tracing the origin of fluids responsible for different diagenetic events, (4) scanning electron microscope analysis of various dolomites to determine reservoir quality of the dolomites as a function of diagenetic history, (5) fluid inclusion evaluation to determine the temperatures of secondary dolomite formation and the salinity of the original brines, and (6) analysis of the bitumen plugging pore throats.

Reservoir diagenetic fabrics and porosity types of these carbonate buildups were analyzed to (1) determine the sequence of diagenetic events, (2) predict facies patterns, and (3) provide data input for reservoir modeling studies. Diagenetic characterization focused on reservoir heterogeneity, quality, and compartmentalization within the field. All depositional, diagenetic, and porosity information will be combined with the production history in order to analyze the potential for the Leadville Limestone regionally.

Results

An ideal diagenetic sequence based on our analysis of Leadville thin sections from Lisbon field is presented in figure 15. The early diagenetic history of the Leadville sediments, including some early dolomitization and leaching of skeletal grains, resulted in low-porosity and/or low-permeablility rocks. Most of the porosity and permeability associated with hydrocarbon production was developed during deeper subsurface dolomitization and dissolution. Some of these important subsurface processes are shown with the purple bars in figure 15 and are discussed below generally in the order in which they occur.

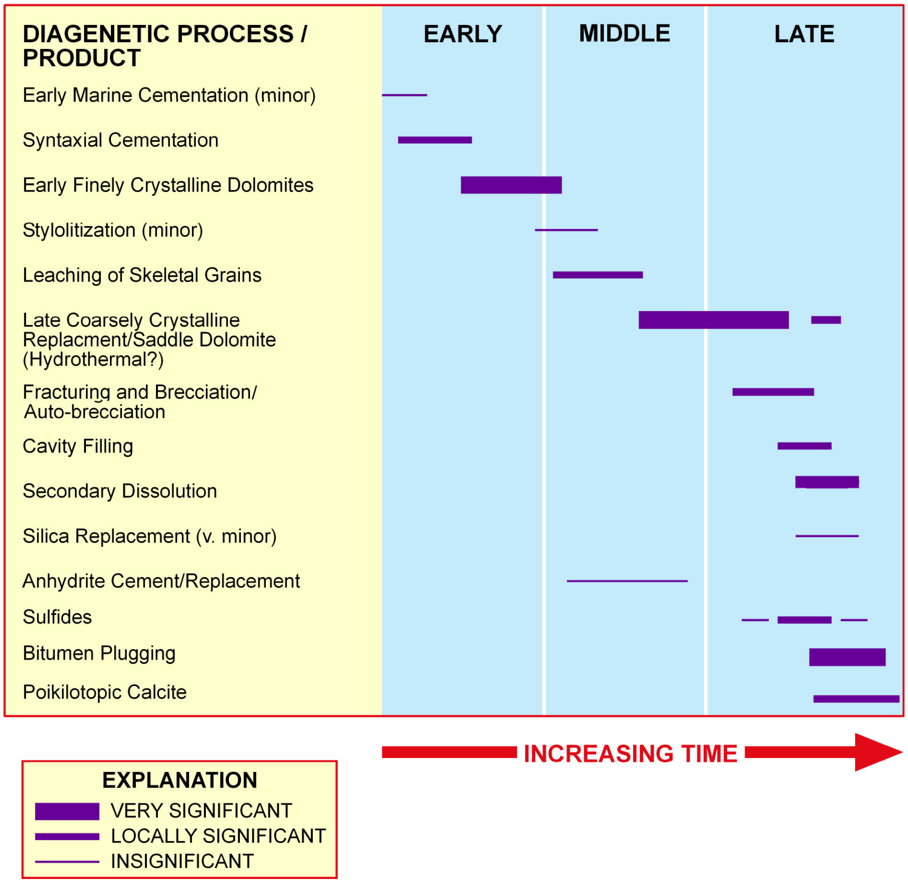


Figure 15. Ideal diagenetic sequence through time based on thin section analysis, Leadville Limestone, Lisbon field.

Syntaxial cement: Syntaxial cementation is an early diagentic event (figure 15). This type of cementation is found exclusively as overgrowths on echinoderms (figure 16), in this case dominantly crinoids deposited in banks or shoals of the open-marine facies. Crinoid ossicles often appear to be "floating" in cement with little evidence of compaction. If extensive syntaxial cementation has occurred, the result will be a significant reduction of porosity. However, from the thin sections evaluated, it appears that this diagenetic process has been relatively minor.

Dolomitization and porosity development: Two basic types of dolomite have been seen within the cores (figure 17A). The first type consists of "stratigraphic" dolomites that preserve original depositional grains and textures. Very fine (<5 μ), interlocking dolomite crystals with no intercrystalline pore spaces are the norm (figure 17B). Commonly, this type of dolomite can be correlated across the field in several relatively thin intervals. The second type of dolomite is a much coarser (>10-20 μ), later replacement of all types of limestone and earlier "stratigraphic" dolomites (figure 17C). Crosscutting relationships with carbonate bedding and variable dolomite thickness across the field are common. Petrographically, the coarse, second dolomite type consists of crystals with thick, cloudy, inclusion-rich cores and thin, clear overgrowths with planar crystal terminations. Often, these coarser dolomites show saddle dolomite characteristics of curved crystal shape (figure 18) and sweeping extinction under cross-polarized lighting. Predating or concomitant with saddle dolomite formation, are pervasive leaching and dissolution episodes that crosscut the carbonate host rocks, and result in

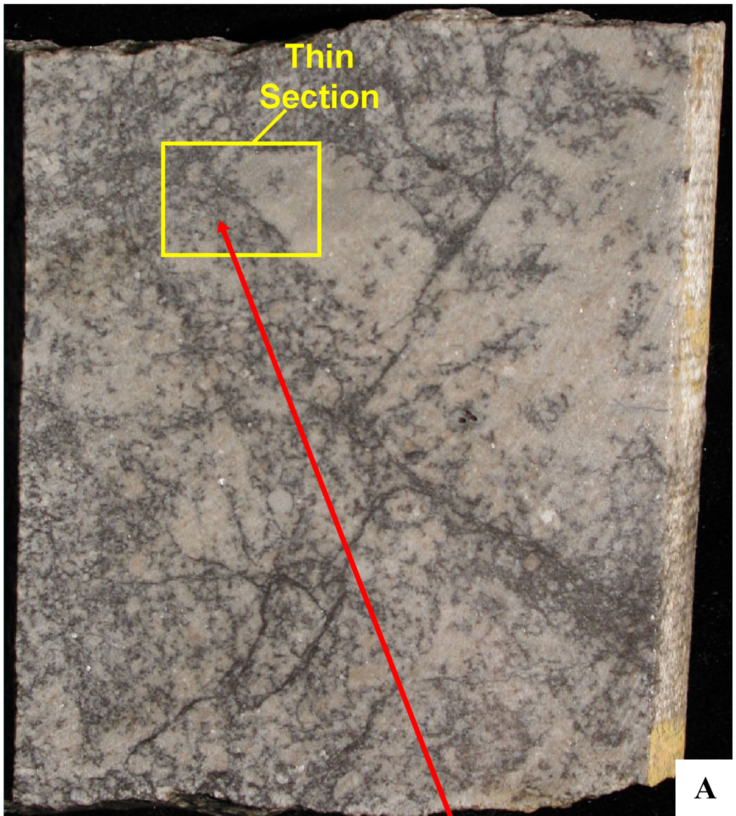
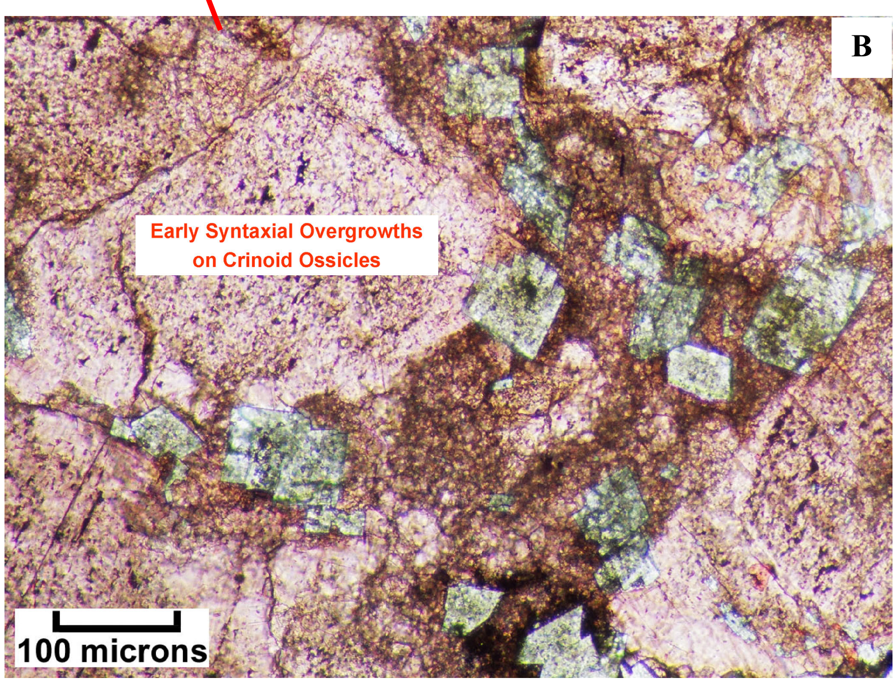


Figure 16. (A) Conventional core slab showing partially dolomitized crinoidal/grainstone packstone. (B) Representative photomicrograph (plane light) from the core in A, showing early syntaxial overgrowths on crinoid ossicles. Crinoids appear cloudy due to inclusions of organic matter. Lisbon No. D-816 well (figure 5), 8435 feet, porosity = 7.5 percent, permeability = 0.03 mD.



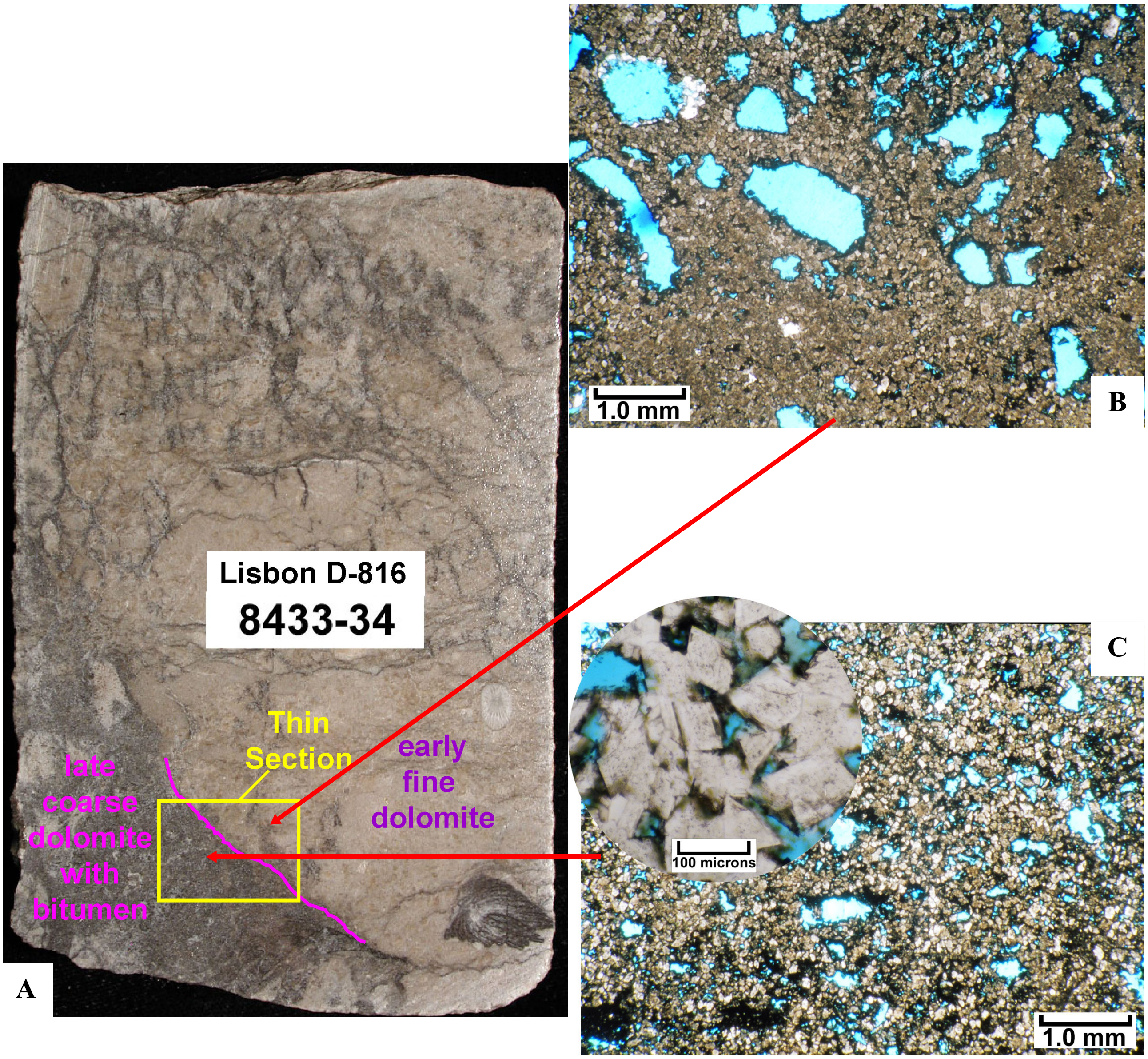


Figure 17. (A) Conventional core slab showing tight, fabric selective, very fine early dolomite as well as porous, coarser late dolomite. Most of the late dolomite crystal faces are coated with films of pyrobitumen. Hence, most of the areas of crosscutting coarser dolomites are black in this view. Note the position of the thin section which captures the contact between low-permeability early dolomite (upper right part of the thin section box) and high-permeability late, "black dolomite" (lower left). (B) Representative photomicrograph (plane light) of the tight, finely crystalline dolomite with isolated grain molds. Most of this fabric selective dolomite formed early in the diagenetic history of the skeletal/peloid sediment. (C) Representative photomicrograph (plane light) of the coarser, replacement dolomite (both euhedral rhombs and occasional "saddle" overgrowths [close-up view in inset]). The black (opaque) areas are the result of pyrobitumen films and minor sulfide precipitation. Lisbon No. D-816 well (figure 5), 8433 feet, porosity = 2 percent, permeability <0.1 mD.

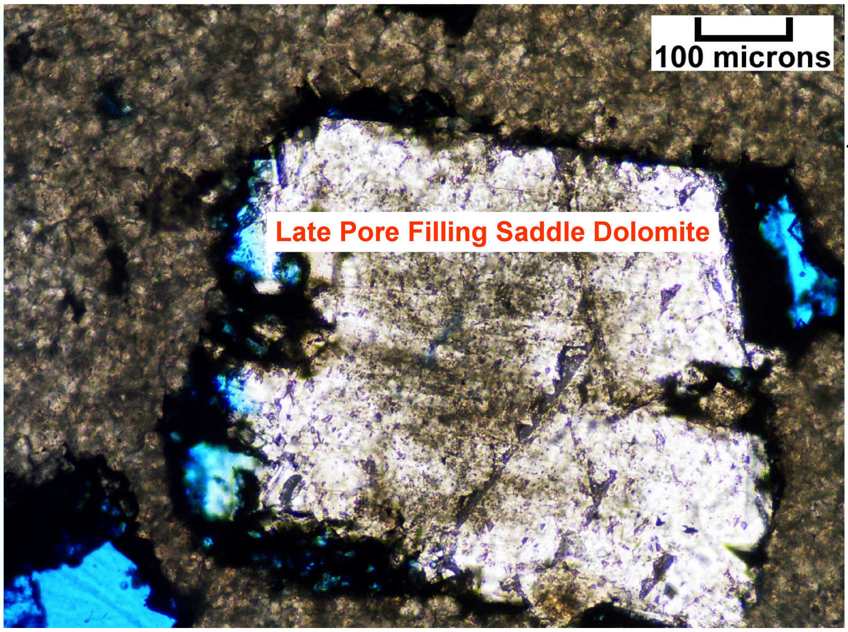


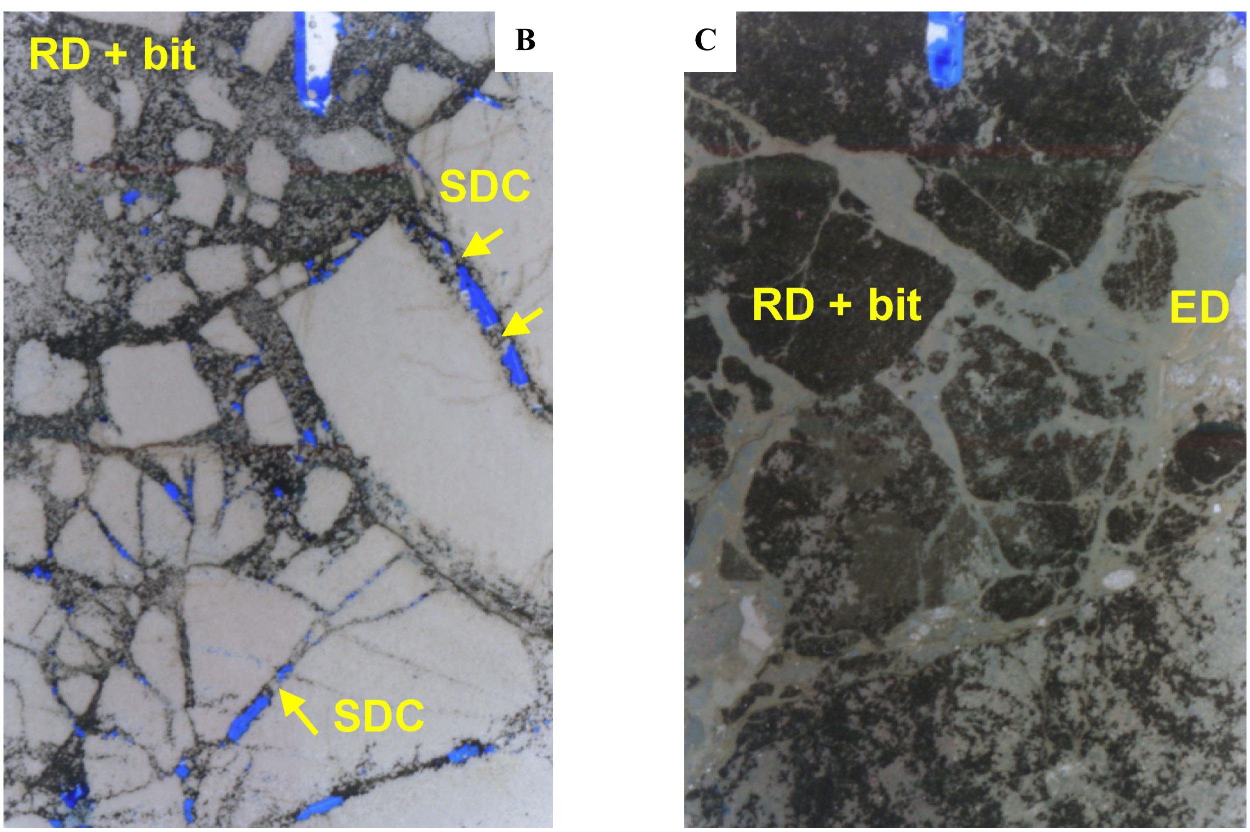
***Figure 18.** Thin section photomicrograph (plane light) showing a saddle dolomite cement that is filling a large pore (either a grain mold or small vug). The dolomite cement has been surrounded by a coating of pyrobitumen (in black). It appears that this late dolomite cement has been partially dissolved or corroded around its margins after the bitumen coating. Lisbon No. D-816 well (figure 5), 8421 feet, porosity = 8.3 percent, permeability = 34 mD.*

late vugs, as well as extensive microporosity. Pyrobitumen appears to coat most intercrystalline dolomite, as well as dissolution pores associated with the second type of dolomite. Most reservoir rocks within Lisbon field appear to be associated with the second, late type of dolomitization and associated leaching events.

Later dolomitization, saddle dolomite, and dolomite cement precipitation may have occurred at progressively higher temperatures, that is, hydothermal dolomite. Hydrothermal events can improve reservoir quality by increasing porosity through dolomitiztion, leaching, development of microporosity, and natural fracturing (forming breccia) kept open with various minerals (Smith, 2004). Hydrothermal dolomite precipitates under temperature and pressure conditions greater than the ambient temperature and pressure of the host limestone (Davies, 2004). The result can be the formation of large, diagenetic-type hydrocarbon traps. Further geochemical analysis is planned to confirm the presence of hydrothermal dolomite in the Leadille Limestone at Lisbon field and the reservoir potential it would imply for the Paradox Basin.

Post-burial brecciation: Fracturing and brecciation are quite common within Lisbon field (figure 19 through 21). However, brecciation is most commonly caused by hydrofracturing, creating an explosive looking, pulverized rock. The result yields an “autobreccia” as opposed to a collapse breccia. Clasts within an autobreccia have basically remained in place and moved very little. Dolomite clasts are often surrounded by solution-enlarged fractures partially filled with coarse rhombic and saddle dolomites that are coated with pyrobitumen. Areas between clasts can exhibit very good intercrystalline porosity or microporosity or they may filled by low-porosity saddle dolomite cement. Intense bitumen plugging is concurrent or takes place shortly after brecciation. “Reike,” or stair-step fractures, are occasionally present, reflecting shear and the explosive fluid expulsion from the buildup of pore pressure.

Figure 19. (A) Conventional core slab showing a dolomite "autobreccia" in which the clasts have moved very little. The black material surrounding the in-place clasts is composed of porous late dolomite coated with pyrobitumen. (B) Entire thin section overview from the core in A, showing low-porosity, white dolomite clasts surrounded by solution-enlarged fractures partially filled with coarse rhombic (RD) and saddle dolomites that are coated with pyrobitumen (bit). These black areas between the clasts exhibit very good intercystalline porosity. The open fracture segments (in blue) between clasts are bridged by coarse, saddle dolomite cements (SDC). (C) Entire thin section overview from the core in A, of black, porous, dolomite clasts surrounded in this case by coarse, low-porosity saddle dolomites. These white dolomites were probably early dolomite (ED) filling space between possible "hydrofactured" replacement dolomites. The black porous dolomites are mostly rhombic (planar) dolomites (RD) coated with thin films of pyrobitumen (bit). Lisbon NW USA No. B-63 well (figure 5), 9938.3 feet, porosity = 6.4 percent, permeability = 54 mD.



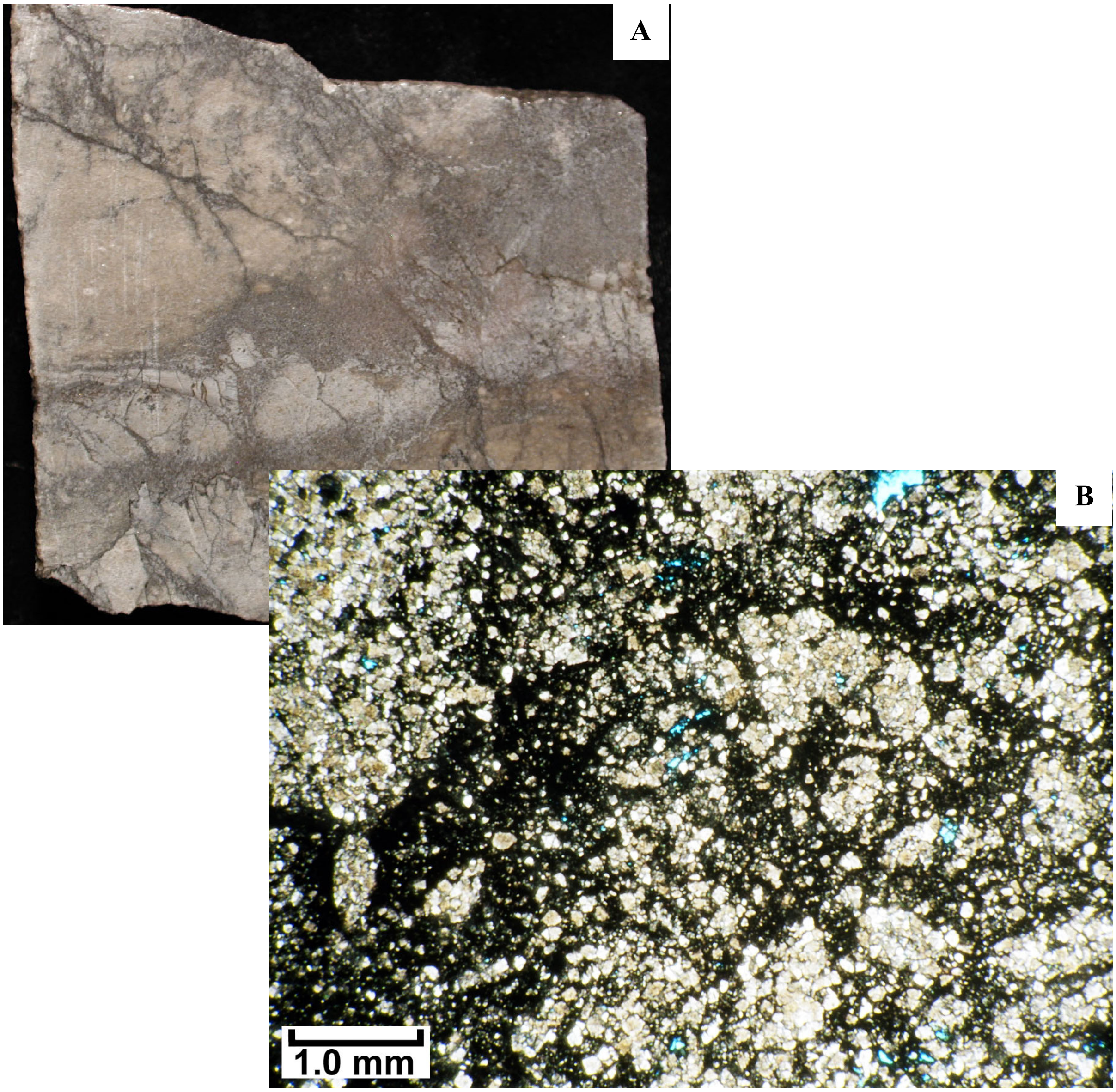


Figure 20. (A) Conventional core slab of a dolomitized, peloidal/crinoidal packstone/ wackestone with swarms of fractures marked by black, coarse dolomite. (B) Representative photomicrograph (plane light) from the core in A, showing highly deformed and brecciated dolomite within a bitumen-lined fracture zone. Lisbon No. D-816 well (figure 5), 8438.5 feet, porosity = 11 percent, permeability = 5 mD.

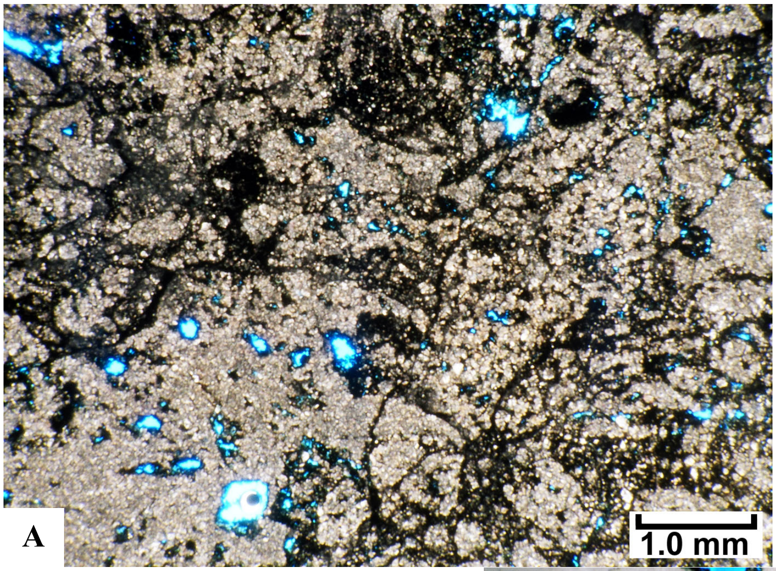
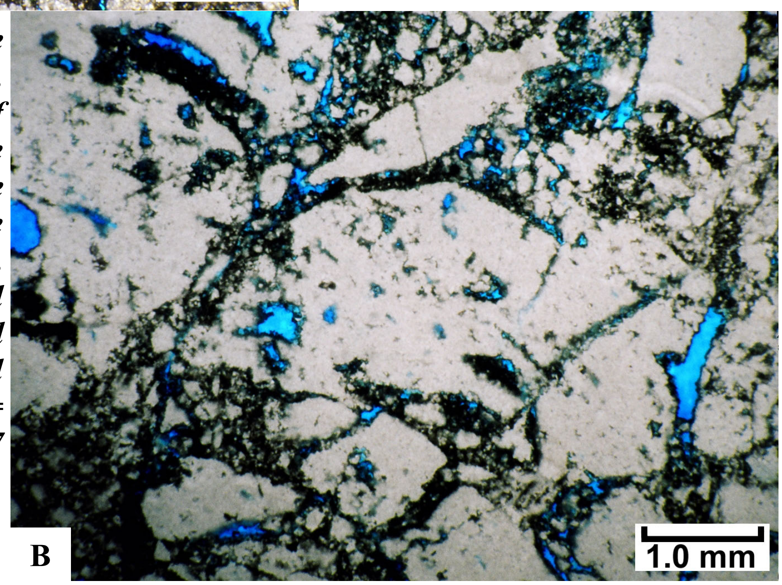


Figure 21. (A) Representative photomicrograph (plane light), showing another example of intensely brecciated dolomite within a bitumen-lined fracture zone. (B) Representative photomicrograph (plane light), showing large autoclasts and bitumen in an intensely brecciated dolomite. Lisbon No. D-816 well (figure 5), 8423 feet, porosity = 10.5 percent, permeability = 47 mD.



<u>Karst-related processes:</u> Sediment-filled cavities are relatively common throughout the upper third of the Leadville in Lisbon field (figure 22). These cavities or cracks were related to karstification of the exposed Leadville (figure 8). Infilling of the cavities by detrital carbonate and siliciclastic sediments occurred before the deposition of the Pennsylvanian Molas Formation. The contact between the transported material and the country rock can be sharp, irregular, and corroded with small associated mud-filled fractures. The transported material consists of poorly sorted detrital quartz grains (silt size), chert fragments, carbonate clasts, clay, and occassional clasts of mud balls (desiccated and cracked). The carbonate muds infilling the karst cavities are largely dolomitized (a later diagenetic process), very finely crystalline, and non-porous. The infilling sometimes displays a crude layering.

Other karst features observed in Leadville thin sections include the presence of “root hair” – thin, sinuous cracks filled with dolomitized mud. Clasts also may have a coating of clay. Both of these features are evidence of a possible, nearby soil zone.

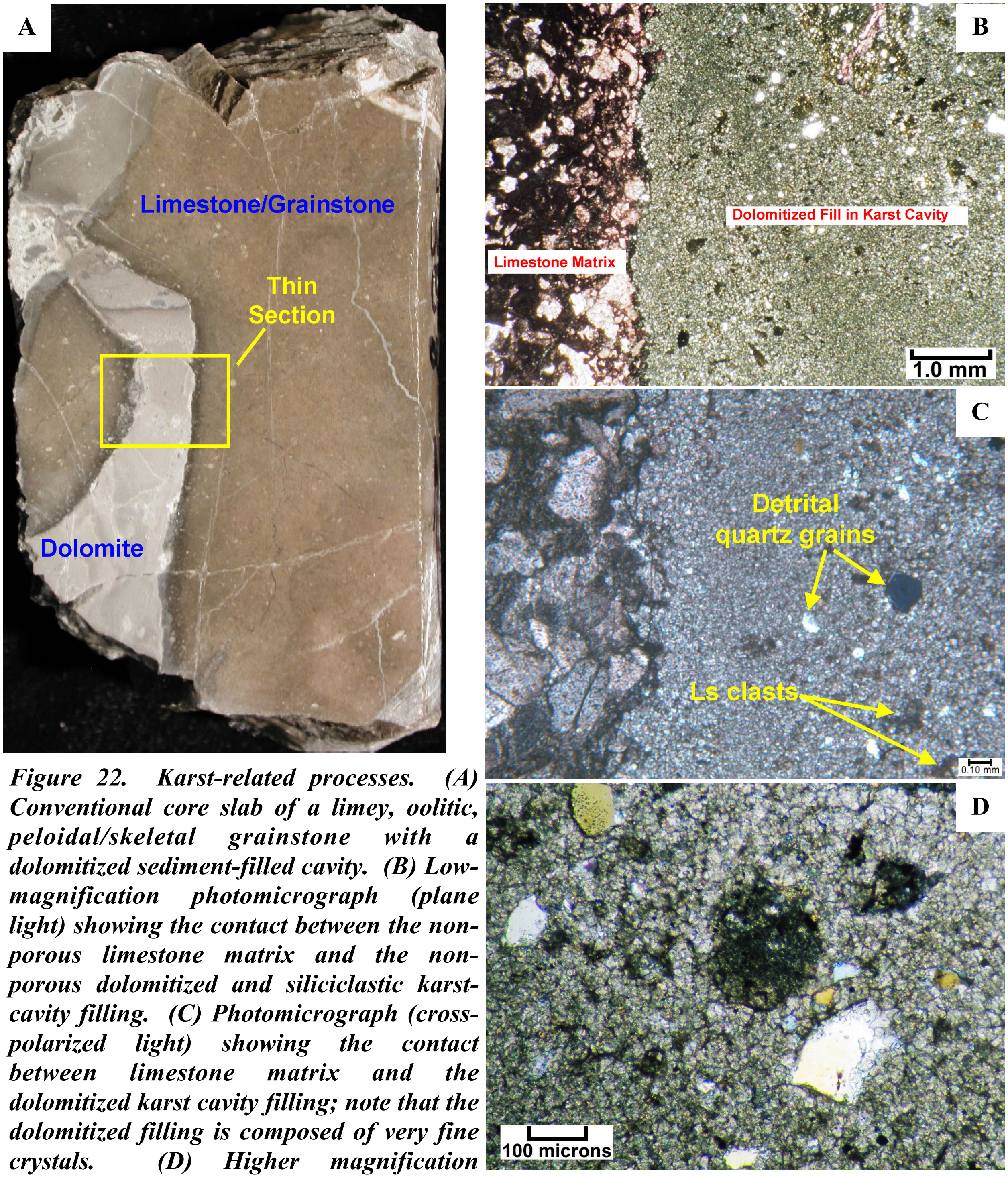


Figure 22. Karst-related processes. (A) Conventional core slab of a limey, oolitic, peloidal/skeletal grainstone with a dolomitized sediment-filled cavity. (B) Low-magnification photomicrograph (plane light) showing the contact between the non-porous limestone matrix and the non-porous dolomitized and siliciclastic karst-cavity filling. (C) Photomicrograph (cross-polarized light) showing the contact between limestone matrix and the dolomitized karst cavity filling; note that the dolomitized filling is composed of very fine crystals. (D) Higher magnification photomicrograph (plane light) of detrital quartz grains (white) and small carbonate clasts (dark gray) within the tight, dolomitized mud filling the karst cavity. Lisbon No. D-616 well (figure 5), 8308-8309 feet, porosity = 1.2 percent, permeability = 11.1 mD.

Anhydrite and sulfides: Dissolution pores (molds) and pore throats are sometimes plugged or bridged by lathes of late anhydrite cement (figure 23). In the photomicrographs studied, complete plugging of porosity was rare and the overall presence of anhydrite cement and replacement was relatively insignificant for the Leadville Limestone in the Lisbon reservoir rocks.

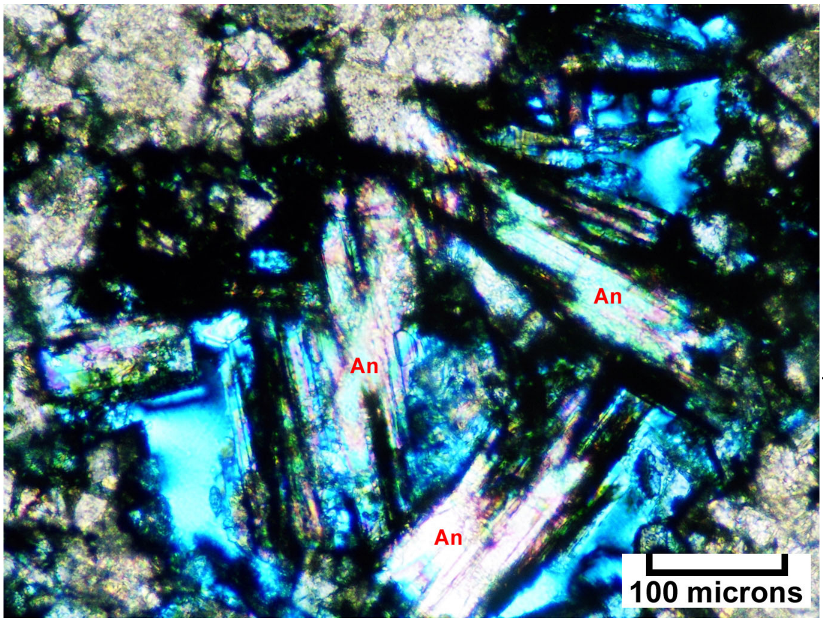


Figure 23. Representative photomicrograph (cross-polarized light) showing lathes of late anhydrite cement (An, in the pastel colors) filling a dissolution pore. The unfilled portions of the pore are seen in the blue areas. Lisbon No. D-816 well (figure 5), 8426-8431 feet, porosity = 11.1 percent, permeability = 15 mD.

Possible sulfide minerals are observed in several Leadville thin sections (figure 24). They appear as small, angular, brassy crystals. They tend to line moldic pores or form on, and between, rhombic dolomite crystals. These minerals may be associated with hydrothermal fluids responsible for the coarse saddle dolomites. They may also be related to copper mineralization found a few miles to the east at the Lisbon Valley copper mine. The copper deposit includes fracture filling and disseminated copper sulfides (chalcocite, bornite, and covellite) replacing dead oil and pyrite (J.P. Thorson, Summo Minerals, verbal communication, September 20, 1996). The exact nature and composition of the sulfide minerals at Lisbon field is unknown and will be examined in closer detail with the scanning electron microscope later in the reservoir characterization.

Late macrocalcite: Macrocalcite, also referred to as poikilotopic calcite, is viewed as late, large, slow-growing crystals (figure 25), and although not extensive in the Leadville at Lisbon field, its presence provides some significant insight into the diagenetic history of these rocks. The example shown in figure 25 shows an autobreccia that retains small amounts of early, finely crystalline (tight) dolomite replaced by "mini-saddles" and medium crystalline (euhedral) dolomite. Early during this samples' history, it once had intercrystalline porosity that was enhanced by dissolution to form additional pores. Subsequently, the pores were partially filled with coarsely crystalline saddle dolomite and bitumen. Finally, the remaining solution-enlarged pores were occluded by poikilotopic calcite. Poikilotopic calcite may have formed as oil-field water rose following the gas/condensate cap.

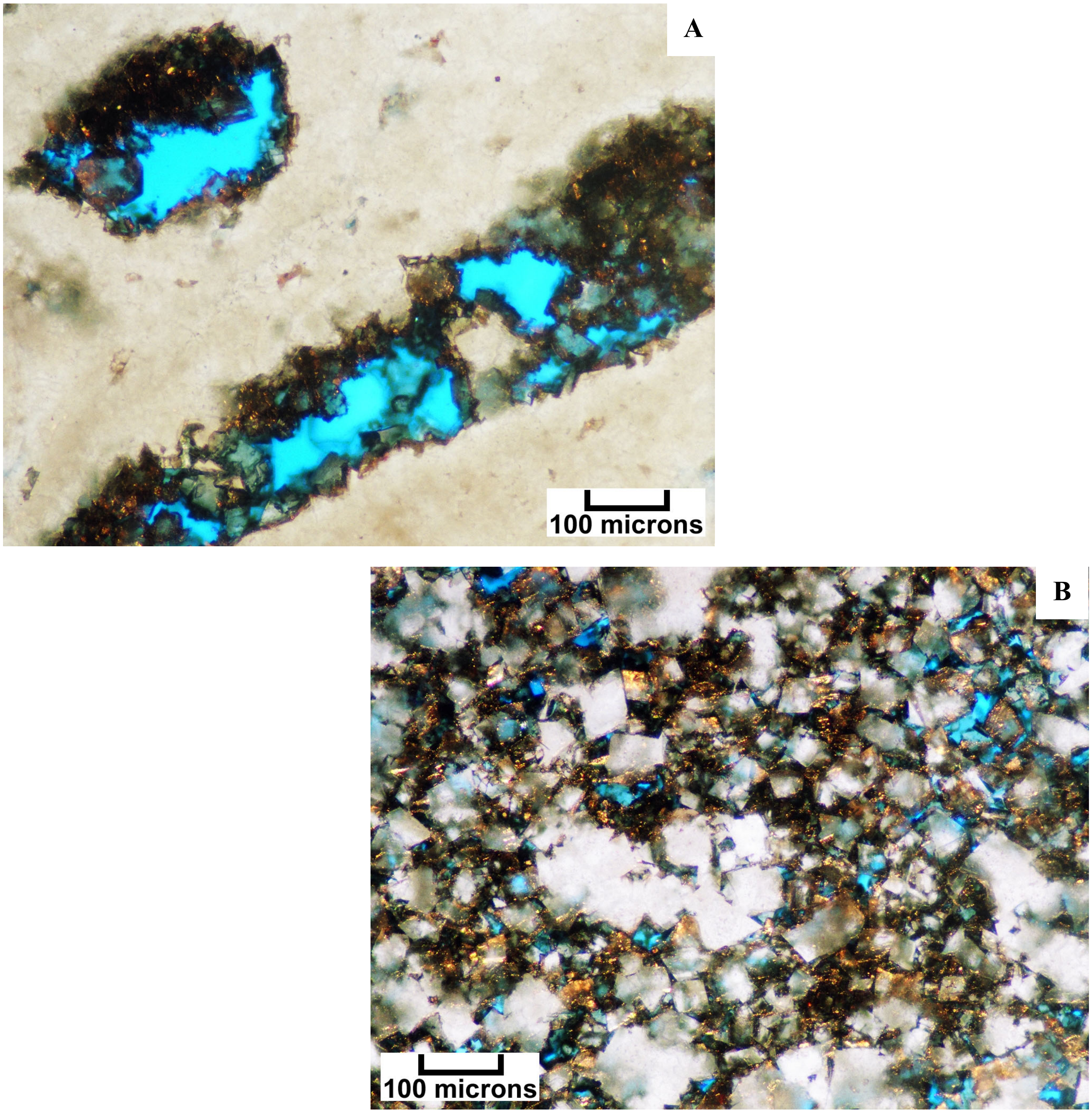


Figure 24. Possible sulfide mineralization within the Leadvlle Limestone at Lisbon field. (A) Photomicrograph ("white card" and reflected light) showing moldic pore lined with black pyrobitumen and possible sulfide minerals (small brassy crystals). Lisbon No. D-816 well (figure 5), 8444-8445 feet, porosity = 6.6 percent, permeability = 7 mD. (B) Photomicrograph ("white card" and reflected light) showing black pyrobitumen and sulfide minerals on and between rhombic dolomite crystals (in white and light gray). Lisbon No. D-816 well (figure 5), 8446-8447 feet, porosity = 13 percent, permeability = 59 mD.

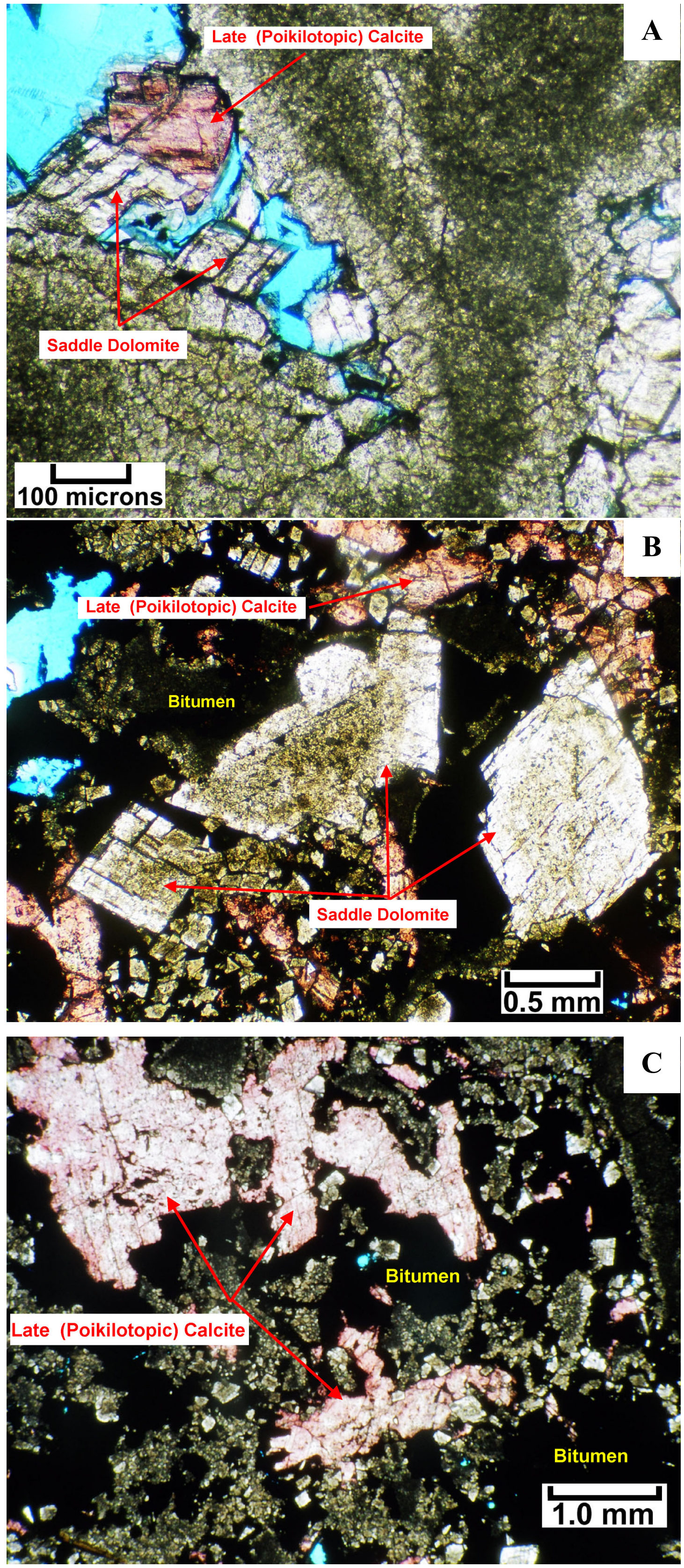


Figure 25. (A) Photomicrograph (plane light) showing saddle dolomite crystals and a single late macrocalcite crystal (stained red) filling a portion of a large dissolution pore (blue) in a finely crystalline dolomite matrix. Northwest Lisbon No. B-63 well (figure 5), 9991.8 feet, porosity = 6.2 percent, permeability = 0.3 mD. (B) Photomicrograph (plane light) showing coarse rhombic and saddle replacement dolomite that displays cloudy cores and clear rims. Dissolution pores are filled with pyrobitumen (black) and late macrocalcite (stained red). An additional episode of dissolution can be seen as the open (blue) pores that appear to post-date most of the pyrobitumen emplacement. (C) Dissolution pores filled completely with bitumen (black) and late macrocalcite (stained red) that resemble saddle dolomite molds. B and C from Northwest Lisbon No. B-63 well (figure 5), 10,004-10,005 feet, porosity = 14.4 percent, permeability = 1.9 mD.

Porosity and Permeability Cross Plots

Porosity and permeability data from core plugs were obtained from the five well cores described (table 2). Cross plots of these data are used to (1) determine the most effective pore systems for oil storage versus drainage, (2) identify reservoir heterogeneity, (3) predict potential untested compartments, (4) infer porosity and permeability trends where core-plug data are not available, and (5) match diagenetic processes, pore types, mineralogy, and other attributes to porosity and permeability distribution. Porosity and permeability cross plots were constructed using the available data.

Figure 26 is a representative set of core analyses from the Leadville Limestone in Lisbon field. The dominant pore types are intercrystalline, moldic, fracture, and channel. The plot shows two distinct populations of dolomites with respect to permeability and petrographic character. The early, finely crystalline dolomites (with or without isolated molds) display low permeability. The coarser, late dolomites (with or without late dissolution) display high permeability. In addition, analysis of the plot shows that those zones that have been dolomitized have better reservoir potential than those that remain limestone, even where the limestone has been fractured and brecciated.

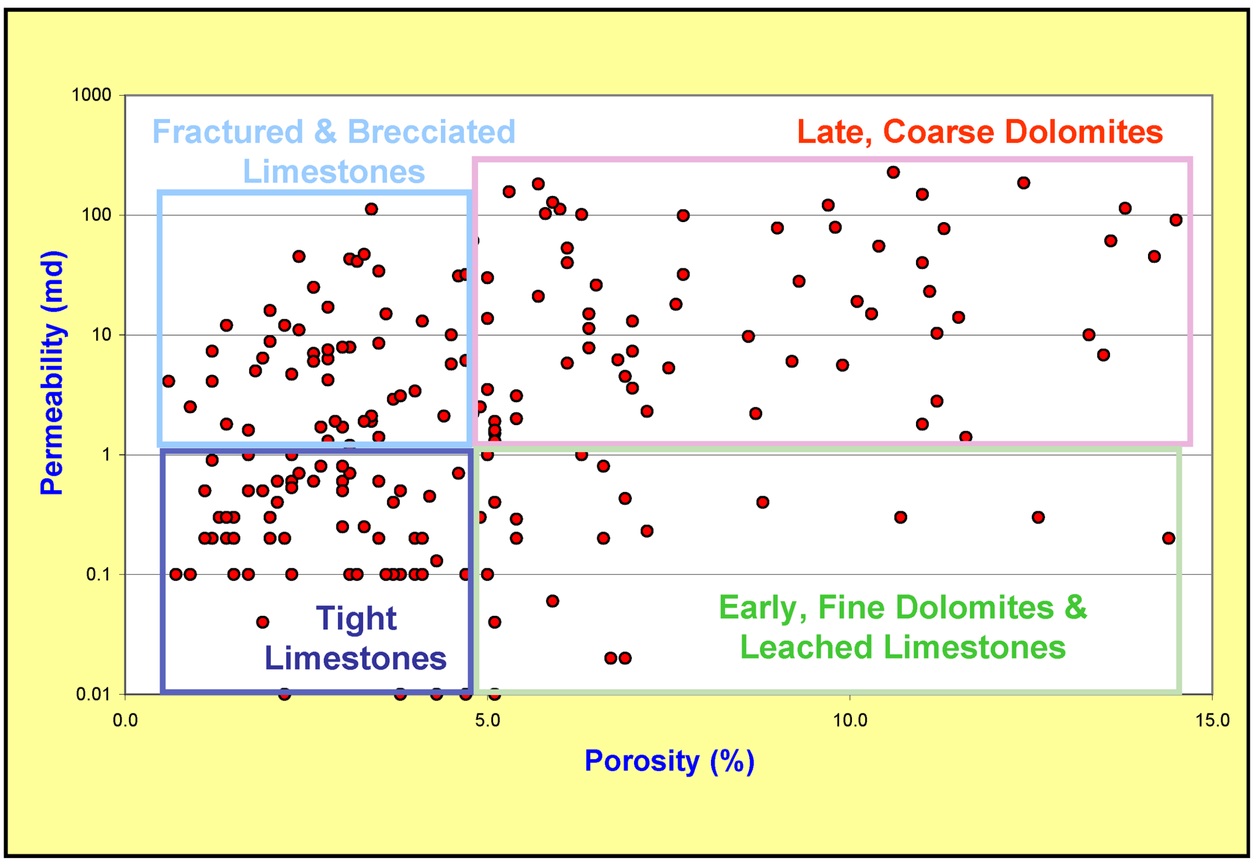


Figure 26. Lisbon Unit No. B-610 well permeability versus porosity cross plot by diagenesis.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for the Leadville Limestone project, described in this report. All maps, cross sections, lab analyses, reports, databases, and other deliverables produced for the project will be published in interactive, menu-driven digital (Web-based and compact disc) and hard-copy formats by the UGS for presentation to the petroleum industry. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*. This information will also be released through the UGS periodical *Survey Notes* and be posted on the UGS Paradox Basin project Web page.

The technology-transfer plan includes the formation of a Technical Advisory Board and a Stake Holders Board. These boards meet annually with the project technical team members. The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of Leadville field operators and those who are actively exploring for Leadville hydrocarbons in Utah and Colorado. This board ensures direct communication of the study methods and results to the operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the State of Utah (School and Institutional Trust Lands Administration, and Utah Division of Oil, Gas and Mining) and the federal government (Bureau of Land Management). The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports, copies of all publications, and other material resulting from the study. Board members also provide field and reservoir data. The project technical team met with Technical Advisory and Stake Holders Boards in Denver, Colorado, on August 12, 2004. Project goals, activities, and results were presented as well as a mini core workshop of Leadville core from Lisbon field.

Project materials, plans, objectives, and results were displayed at the UGS booth during the AAPG Annual Convention, April 18-24, 2004, in Dallas, Texas, and at the AAPG Rocky Mountain Section Meeting/Rocky Mountain Natural Gas Strategy Conference and Investment Forum (hosted by the Colorado Oil & Gas Association), August 9-11, 2004, in Denver, Colorado. Four UGS scientists staffed the display booth at these events. Project displays will be included as part of the UGS booth at professional meetings throughout the duration of the project.

Utah Geological Survey *Survey Notes* and Web Site

The UGS publication *Survey Notes* provides non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision-makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals specifically interested in the Leadville project or other DOE-sponsored UGS projects. They receive *Survey Notes* and notification of project publications and workshops.

The UGS maintains a Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Oil, Gas, Coal, & CO_2*, which describes the UGS/DOE cooperative studies past and present (PUMPII, Paradox Basin [two projects evaluating the Pennsylvanian Paradox Formation], Ferron Sandstone, Bluebell field, Green River Formation), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The Leadville Limestone project page, http://geology.utah.gov/emp/leadville/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) semi-annual technical progress reports.

Presentations

The following presentations were made during the reporting period as part of the technology transfer activities:

"The Mississippian Leadville Limestone Exploration Play, Utah and Colorado" by Thomas C. Chidsey, Jr., and David E. Eby, AAPG Rocky Mountain Section Meeting/ Rocky Mountain Natural Gas Strategy Conference and Investment Forum (hosted by the Colorado Oil & Gas Association), August 10, 2004, in Denver, Colorado. The talk presented a general overview of the Leadville Limestone, and facies, petrography, and diagenesis of the Lisbon case-study field.

"The Mississippian Leadville Limestone Exploration Play, Grand County, Utah" by Thomas C. Chidsey, Jr., Moab, Utah, May 4, 2004, to the Grand County Council, members of the press, and general public. The petroleum geology of the Paradox Basin and an overview of project goals, activities, and results were part of the presentation.

Project Publications

Chidsey, T.C., Jr., Morgan, C.D., McClure, K., and Eby, D.E., 2004, The Mississippian Leadville Limestone exploration play, Utah and Colorado [abs.]: American Association of Petroleum Geologists, Rocky Mountain Section Meeting Official Program Book, p. 94.

Chidsey, T.C., Jr., Morgan, C.D., and McClure, Kevin, 2004, The Mississippian Leadville Limestone exploration play, Utah and Colorado: exploration techniques and studies for independents – semi-annual technical progress report for the period October 1, 2004 to March 31, 2004: U.S. Department of Energy, DOE/BC15424-1, 26 p.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

1. The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from six fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. Most Leadville oil and gas production is from basement-involved structural traps. All of these fields are currently operated by small, independent producers. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored. Only independent producers continue to hunt for Leadville oil targets in the region.

2. Lisbon field, San Juan County, Utah accounts for most of the Leadville oil production in the Paradox Basin. Its reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the basin. Lisbon was selected as the case-study field for the Leadville Limestone project.

3. Leadville facies include open marine (crinoidal banks or shoals and Waulsortian-type buildups), middle shelf, and restricted marine (peloid and oolitic shoals). Rock units with open-marine and restricted-marine facies constitute a significant reservoir potential, having both effective porosity and permeability when dissolution of skeletal grains followed by dolomitization has occurred.

4. Leadville reservoir quality at Lisbon is greatly enhanced by dolomitization and dissolution of shallow water limestone. There are two basic types of dolomite: (1) very fine, early dolomite, and (2) coarse, late dolomite. Early dolomitization preserves depositional fabrics and has limited porosity development, except for limited dissolution of fossils, and has very low permeabilities. Late dolomitization has two morphologies: rhombic dolomites and saddle dolomites. Most reservoir rocks within Lisbon field appear to be associated with the second, late type of dolomitization and associated leaching events.

5. Pyrobitumen coats most intercrystalline dolomite as well as dissolution pores associated with the second type of dolomite. Fracturing and brecciation caused by hydrofracturing are widespread within Lisbon field. Sediment-filled cavities, related to karstification of the exposed Leadville, are relatively common throughout the upper third of the formation in the field. Other diagenetic products include syntaxial cement, sulfide minerals, anhydrite cement and replacement, and late macrocalcite.

6. Late dolomitization, saddle dolomite, and dolomite cement precipitation, as well as sulfides and brecciation, may have developed from hydrothermal events that can greatly improve reservoir quality. The result can be the formation of large, diagenetic-type hydrocarbon traps. Further geochemical analysis is recommended as part of the Budget Period I reservoir characterization to confirm the presence of hydrothermal dolomite in the Leadville Limestone at Lisbon field and the potential it would imply for the Paradox Basin.

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Core and petrophysical data were provided by Tom Brown, Inc. (now Encana Corp.). James Parker of the Utah Geological Survey (UGS) drafted figures and Cheryl Gustin, UGS, formatted the manuscript. This report was reviewed by David Tabet and Michael Hylland of the UGS.

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